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A Comprehensive Review of the COVID-19 Pandemic and the Role of IoT, Drones, AI, Blockchain, and 5G in Managing Its Impact

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ABSTRACT The unprecedented outbreak of the 2019 novel coronavirus, termed as COVID-19 by the World Health Organization (WHO), has placed numerous governments around the world in a precarious position. The impact of the COVID-19 outbreak, earlier witnessed by the citizens of China alone, has now become a matter of grave concern for virtually every country in the world. The scarcity of resources to endure the COVID-19 outbreak combined with the fear of overburdened healthcare systems has forced a majority of these countries into a state of partial or complete lockdown. The number of laboratory-confirmed coronavirus cases has been increasing at an alarming rate throughout the world, with reportedly more than 3 million confirmed cases as of 30 April 2020. Adding to these woes, numerous false reports, misinformation, and unsolicited fears in regards to coronavirus, are being circulated regularly since the outbreak of the COVID-19. In response to such acts, we draw on various reliable sources to present a detailed review of all the major aspects associated with the COVID-19 pandemic. In addition to the direct health implications associated with the outbreak of COVID-19, this study highlights its impact on the global economy. In drawing things to a close, we explore the use of technologies such as the Internet of Things (IoT), Unmanned Aerial Vehicles (UAVs), blockchain, Artificial Intelligence (AI), and 5G, among others, to help mitigate the impact of COVID-19 outbreak.

INDEX TERMS Coronavirus, COVID-19, pandemic, transmission stages, global economic impact, UAVs for disaster management, Blockchain, IoMT applications, IoT, AI, 5G.

I. INTRODUCTION

The COVID-19, an acronym for “Coronavirus Disease-2019”, is a respiratory illness caused by the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), a contagious virus belonging to a family of single-stranded, positive-sense RNA viruses known as coronaviridae. Much like the influenza virus, SARS-CoV-2 attacks the respiratory system and causes ailments such as cough, fever, fatigue, and breathlessness. While the exact source of the virus is unknown, scientists have mapped the genome sequence of the

SARS-CoV-2 and determined it to be a member of the β -CoV genera of the coronavirus family, which typically derives its gene sources from bats and rodents [1]. The COVID-19 was first reported to affect human life in Wuhan City, in the Hubei province of China in December 2019. Since then, the COVID-19 has spread like wildfire throughout the rest of the world, marking its presence in 213 countries and independent territories. COVID-19 statistics for the worst affected countries and regions of the world have been presented in Fig. 1. According to the WHO, the current global tally¹ of confirmed coronavirus cases stands at 3,090,445 while the death toll

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¹as of 30 April 2020

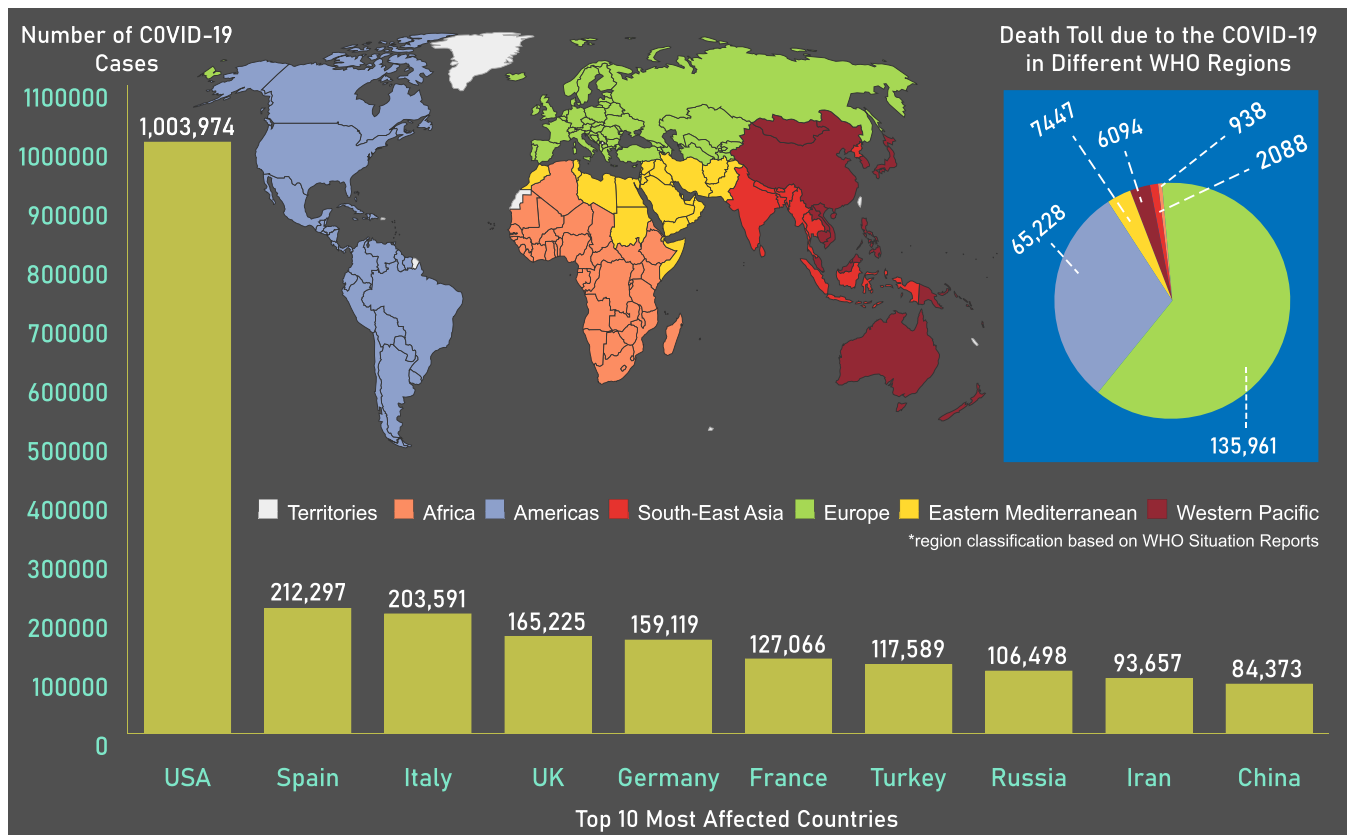


FIGURE 1. Statistics in regards to the COVID-19 (Data Source: WHO Situation Report - 30 April 2020 [3]).

has reached 217,769 [2]. The rapid rise in the number of COVID-19 incidents worldwide has prompted the need for immediate countermeasures to curb the catastrophic effects of the COVID-19 outbreak. To this end, this paper evaluates the use of varied technologies such as IoT, UAVs, AI, blockchain, and 5G, which could help mitigate the adverse effects of this pandemic and expedite the recovery process. However, before exploring the potential technological solutions for COVID-19 pandemic impact management, we provide a comprehensive review of the COVID-19, including its clinical features, diagnosis, treatment, and the impact of its outbreak on the global economy.

A. BACKGROUND

According to the WHO, viral infections, particularly the ones caused by different coronaviruses, continue to emerge and pose a severe public health problem [1]. Coronaviruses are spherical positive-sense RNA viruses ranging from 600Å - 1400Å in diameter [4], with proteins known as spikes protruding from its surface, which impart a crown-like structure to them under the electron microscope. The past two decades have witnessed the emergence of several viral outbreaks with different forms of coronavirus at the helm, such as the 2002-2004 SARS-CoV outbreak [5], and the more recent middle east respiratory syndrome coronavirus (MERS-CoV) infection of 2012. The SARS-CoV outbreak originated in the Guangdong province of China and later

spread to more than 37 countries worldwide, causing over 8000 infections and around 774 deaths [6]. The first case of MERS-CoV infection was detected in Saudi Arabia, which initiated a large-scale outbreak in the middle eastern countries that ultimately led to 871 fatalities [7], [8].

The COVID-19 outbreak came to light on 31 December 2019 when 27 cases of pneumonia of unknown etiology were reported at the WHO's country office in China. For the entire timeline of events, kindly refer to Fig. 2 [9]. The epicenter of the outbreak was linked to Wuhan's wholesale market for seafood and other exotic animals, including snakes, bats, and marmots [10]. A new strain of a highly contagious β -coronavirus, SARS-CoV-2, has been deemed responsible for the rapid outbreak of COVID-19. Distinguishing characteristics of the virus include its extremely contagious nature and relatively long (1-14 days) incubation period. During this period, a person can be infected by the virus and not show any symptoms at all. Therefore, people infected with the disease may unknowingly serve as silent carriers of the virus, contributing to a high basic reproductive number² for the COVID-19 virus. While some studies indicate that SARS-CoV-2 could be susceptible to heat and ultraviolet (UV) light [1], there is no specific treatment or vaccine for the infection to date, and the management protocols for the disease are evolving as of this writing.

²WHO defines basic reproductive number as the number of secondary infections caused by a single infected individual

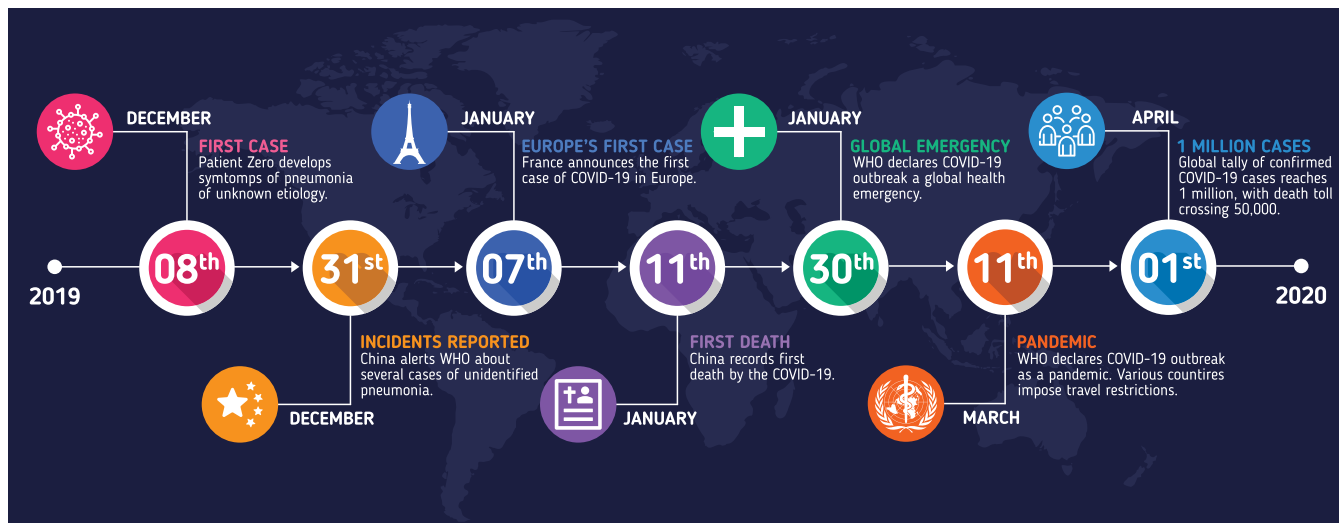


FIGURE 2. A timeline of the COVID-19 pandemic.

B. CLINICAL FEATURES

COVID-19 manifests with clinical features ranging from the asymptomatic state (no symptoms) to acute respiratory distress syndrome (ARDS) and multiple organ dysfunction syndrome (MODS). According to the results of a recent study conducted by the WHO in collaboration with China, of the 55,924 laboratory-confirmed COVID-19 cases that were examined, a majority exhibited clinical characteristics such as fever, dry cough, fatigue, and sputum production. At the same time, only a handful of patients showcased symptoms such as sore throat, headache, myalgia, and breathlessness, while symptoms such as nausea, nasal congestion, hemoptysis, diarrhea, and conjunctival congestion were found to be very rare (refer to Table 1). While most of the COVID-19 patients developed a mild to moderate disease, a few patients were diagnosed with a severe (13.8%) and a critical (6.1%) form of the same [11]. Patients with a severe or a critical form of the disease often develop bluish lips/face and are prone to a variety of complications, including ARDS, acute heart injury, and secondary infection. According to the US Centers for Disease Control and Prevention (CDC), the individuals at the highest risk for severe illness from the COVID-19 include older adults (people above the age of 60) and people with existing medical conditions, such as diabetes, hypertension, asthma, and cardiovascular disease [12].

C. TRANSMISSION MECHANISM

Although there are several studies in the direction of COVID-19's pathophysiological properties, its propagation mechanism remains somewhat elusive. While the initial COVID-19 cases were associated with the direct exposure of individuals to infected animals, the rapid outbreak of the disease has shifted the focus of the research to human-to-human transmission. An analysis of around 75,465 cases of COVID-19 in China has revealed that the COVID-19 virus is

TABLE 1. List of COVID-19 symptoms.

Most Common Symptoms	
Fever	87.9%
Dry Cough	67.7%
Fatigue	38.1%
Sputum Production	33.4%
Less Common Symptoms	
Shortness of Breath	18.6%
Myalgia / Arthralgia	14.8%
Sore Throat	13.9%
Headache	13.6%
Chills	11.4%
Rare Symptoms	
Nausea	5.0%
Nasal Congestion	4.8%
Diarrhea	3.7%
Hemoptysis (coughing up blood)	0.9%
Conjunctival Congestion	0.8%

Source: WHO

primarily transmitted between people from the spread of respiratory droplets through sneezing and coughing [13]. These respiratory droplets have the potential to cover a distance of up to 1.8 meters (6 feet). Therefore, any person in close contact with an infected person is at risk of being exposed to the respiratory droplets, and by extension, the virus. Although symptomatic people have been identified to be the primary source of SARS-CoV-2 transmission, there is also a possibility of transmission via asymptomatic people. Direct and indirect contact with infected surfaces has been identified as another potential cause of COVID-19 transmission. Evidence suggests that the virus can survive on plastic and steel sur-

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FIGURE 3. Organization of this work.

faces for as long as three days, on copper for approximately 4 hours, and up to 24 hours on cardboard [14].

Once the virus enters into a healthy body, it passes through the nasal passage to the mucus membranes present in the throat and binds itself to the body's cellular receptors. With the help of the spikes present on its surface, the SARS-CoV-2 ruptures the cell membrane and forces the cell into making multiple copies of itself. These newly generated copies burst out of the cell and infect other cells in the body. Following this, the virus moves down the bronchial tubes and reaches the lungs, where it severely impairs the host's air sacs [15].

D. ORGANIZATION

The rest of the paper is organized as follows. In section II, we address the existing works that have reviewed the state of the COVID-19 pandemic. In Section III, we present a brief overview of the pandemics that have occurred in the past century. In Section IV, we discuss the different stages of the COVID-19 transmission, while in Section V, the global impact of the outbreak on different sectors of the economy has been evaluated. Section V also includes some statistics providing valuable insights into the widescale impact of the COVID-19 pandemic on these sectors. In Section VI, we discuss the current methods for COVID-19 diagnosis. Section VII examines the efforts being made by various organizations and laboratories in the direction of COVID-19 vaccine & drug development, while Section VIII lists the preventive measures required to safeguard oneself against the COVID-19. In the next nine sections, we provide a compre-

hensive review of the use of technologies such as IoT, UAVs, robots, smart wearables, AI, blockchain, and 5G as a means to manage the outbreak effectively. Finally, Section XVIII concludes the paper. The organization of the paper has also been depicted pictorially in Fig. 3.

II. RELATED WORKS

The massive outbreak of the COVID-19 has prompted various scientists, researchers, laboratories, and organizations around the world to conduct large scale research to help develop vaccines and other treatment strategies. In the months following the COVID-19 outbreak, several papers examining different aspects of the COVID-19 have been published [16]–[22].

To determine the clinical characteristics of the COVID-19, Dawei Wang *et al.* have studied 138 infected patients in Wuhan, China [21]. The authors have taken into account specifics such as demographics, signs & symptoms, and medical history of all the patients to assess their cases carefully. The authors have also presented the laboratory findings of these patients to demonstrate the effects of the SARS-CoV-2 virus on different vital organs of the body. Nanshan Chen *et al.* studied 99 patients with the COVID-19, 49 of whom had a direct link to the Huanan seafood market in Wuhan, known to be the COVID-19 epicenter. Their findings of the epidemiological, clinical, and radiological characteristics of the disease have been published in [22]. In their findings, they report that among all the patients that were studied, 17% developed acute respiratory distress syndrome (ARDS), and among them, 11% died of multiple organ dysfunction syndrome (MODS).

TABLE 2. Major viral diseases (1915 - present).

Disease	Causative Agent	Year(s)	Death Toll	Classification
Spanish Flu	H1N1	1918-1919	~50 million	Pandemic
Asian Flu	H2N2	1957-1958	~1.1 million	Pandemic
Hong Kong Flu	H3N2	1968-1969	~1 million	Pandemic
SARS	SARS-CoV	2002-2004	774	Outbreak
Swine Flu	H1N1 (new strain)	2009-2010	~151,700 to 575,400	Pandemic
MERS	MERS-CoV	2012-present	871*	Outbreak
Asian Lineage Avian Influenza	H7N9	2013-2017	~605	Epidemic
Ebola Virus Disease (EVD)	Zaire ebolavirus	2014-2016	11,325	Epidemic
COVID-19	SARS-CoV-2	2019-present	217,769*	Pandemic

*as of 30 April 2020

Data Source: WHO, CDC

Fang Jiang *et al.* have reviewed six published studies recognizing the clinical characteristics of the COVID-19. In their work, they have summarized these studies and, in doing so, provided a brief overview of clinical features and treatments of the COVID-19 [23]. The authors of [24] have reviewed the existing literature on computed tomography (CT) characteristics of COVID-19 available on platforms such as PubMed, Google Scholar, and Elsevier, among others. The primary issue with both these works is that they review a small subset of a much broader subject. To this end, the authors of [4] and [10] provide a brief overview of the COVID-19 outbreak in terms of its clinical features, prevention, diagnosis, and treatment. Although these surveys shed some light on the current scenario of the COVID-19 outbreak, they give a very brief and limited idea about the exact situation.

Despite the abundance of research in the domain of COVID-19 characteristic analysis and vaccine development, to the best of our knowledge, at the time of this writing, there is no survey that provides a comprehensive review of the COVID-19 outbreak and its potential implications. Furthermore, no work in the existing literature attempts to review the role of emerging technologies such as IoT, UAVs, AI, blockchain, and 5G in managing the COVID-19 pandemic. This presents the need for a detailed survey that provides both the horizontal and the vertical view of the COVID-19 in terms of its clinical features, diagnosis, treatment, prevention strategies, and the technological solutions being adopted to alleviate the impact of its outbreak. In this work, we present a comprehensive review of the COVID-19 pandemic that will help readers gain a deeper understanding of the current global situation due to the COVID-19 pandemic. Before divulging into a thorough analysis of the COVID-19 pandemic, we take a brief look at some of the past pandemics in the section below.

III. PANDEMICS IN THE PAST CENTURY

The last century has seen a plethora of outbreaks and epidemics. While coronaviruses such as SARS-CoV & MERS-CoV have been responsible for a majority of these outbreaks (refer to Table 2), different types of influenza viruses, such as H1N1, H2N2, and H3N2, have been at the

helm of all the four pandemics in the past 105 years. The H1N1 virus alone has been responsible for two pandemics - 1) the Spanish Flu of 1918-1919 and the 2) Swine flu in 2009-2010, while the H2N2 and H3N2 influenza viruses have been responsible for the Asian Flu of 1957-1958, and the Hong Kong flu of 1968-1969, respectively. In this section, we provide an overview of all these pandemics.

A. SPANISH FLU PANDEMIC (1918-1919)

The Spanish Flu is known by many to be the deadliest pandemic in the history of humankind, with the total number of fatalities surpassing the 50 million mark [25]. The disease was caused by the H1N1 virus, which is believed to have originated in birds. Unlike most diseases, Spanish Flu had a peculiar characteristic of being extremely lethal against the young and healthy populace. This was because the virus attacked hosts by causing cytokine storms in the patient's immune system, which often lead to death [26]. Since young people had stronger immune systems as compared to older adults, they were more likely to be affected by the virus.

B. ASIAN FLU PANDEMIC (1957-1958)

The Asian flu pandemic began in February of 1957 in Singapore. It was the second major pandemic of the 20th century after the Spanish Flu pandemic of 1918. It is believed to have caused 116,000 deaths in the US and a total of 1.1 million fatalities worldwide [27]. The virus at the root of this disease was identified to be the type A H2N2 virus, which, like the H1N1, is believed to be of avian origin. Eleven years after the outbreak, the H2N2 virus subsequently mutated to a strain that is no longer able to affect human hosts.

C. HONG KONG FLU PANDEMIC (1968-1969)

The Hong Kong Flu pandemic was the third major influenza pandemic of the 20th century. It was caused by the H3N2 virus, which is believed to have evolved from the H2N2 virus that caused the Asian flu pandemic. The H3N2 virus involved a mutated version of the HA antigen present in H2N2 but retained the same N2 antigen. The impact of the Hong Kong Flu pandemic across the world has

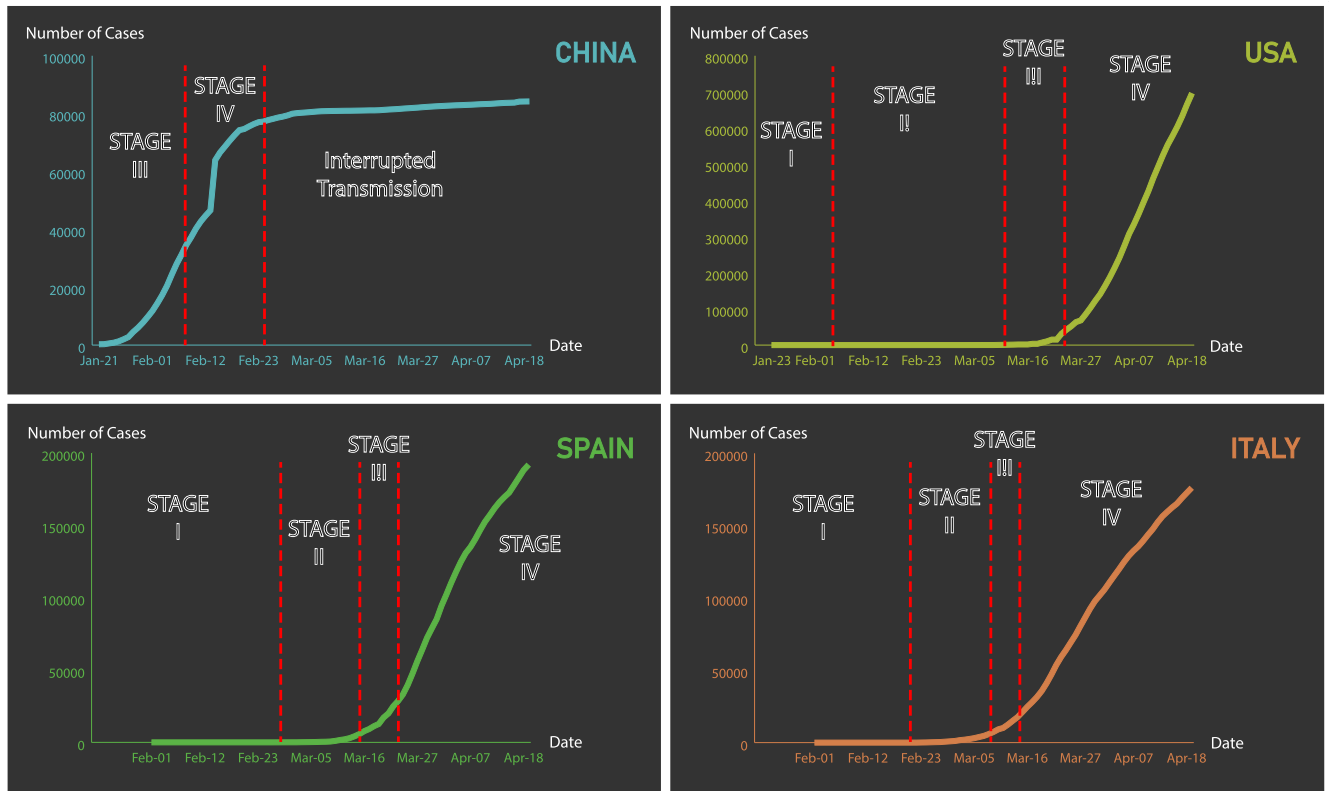


FIGURE 4. Cumulative number of cases of the COVID-19 (data source: WHO situation reports, several media reports).

been described as sporadic, which is believed to have been due to the prior immunity developed against the N2 antigen on account of the Asian Flu pandemic [26]. Unlike the H1N1 virus behind the Spanish Flu pandemic, the H3N2 virus was more aggressive towards people above the age of 65.

D. SWINE FLU PANDEMIC (2009-2010)

In the spring of 2009, a new strain of the type A H1N1 influenza virus emerged, leading to the swine flu pandemic. Like the Spanish Flu, which was caused by a different strain of the same virus, the swine flu pandemic was more deadly against people below 65 years of age. Pre-acquired immunity in older people on account of previous exposure to the H1N1 virus was believed to be one of the reasons for the same. The US Centers for Disease Control and Prevention (CDC) estimate that there have been more than 43.3 million cases, 195,086 hospitalizations, and 8868 deaths in the US alone due to the virus, while the worldwide tally of fatalities stands above 151,700 [28].

IV. DIFFERENT STAGES OF COVID-19 OUTBREAK

According to the WHO, the COVID-19 pandemic is regarded as having four main classes of transmission that remain consistent throughout the world to facilitate better communication and understanding amongst the countries [29]. Such a categorization makes it simpler for other countries to

enforce policies which they think would assist in preventing the outbreak, for example, imposing travel bans, shutting down schools & colleges, and enforcing partial or complete lockdown. For better understanding, we have portrayed the WHO transmission classes as different stages of the COVID-19 outbreak keeping in line with several media reports. The onset of different stages of the COVID-19 outbreak in four countries, namely, China, Spain, Italy, and the USA, have been mapped in Fig. 4.

A. STAGE I - IMPORTED CASES ONLY

The first stage of the COVID-19 outbreak in a particular nation is characterized by its first reported incident of the disease, in this case, COVID-19. In this stage, the disease does not spread locally, and the infection is usually limited to the people with travel history to an already affected region [30].

B. STAGE II - SPORADIC CASES/LOCAL TRANSMISSION

The second stage of the COVID-19 outbreak occurs when there are a few sporadic cases of the disease in the country. It happens when people who are already infected with the disease spread it to people with whom they come into contact, usually immediate family members, friends, and colleagues. At this stage, it is possible to perform contact tracing and limit the spread of the disease by quarantining the infected people.

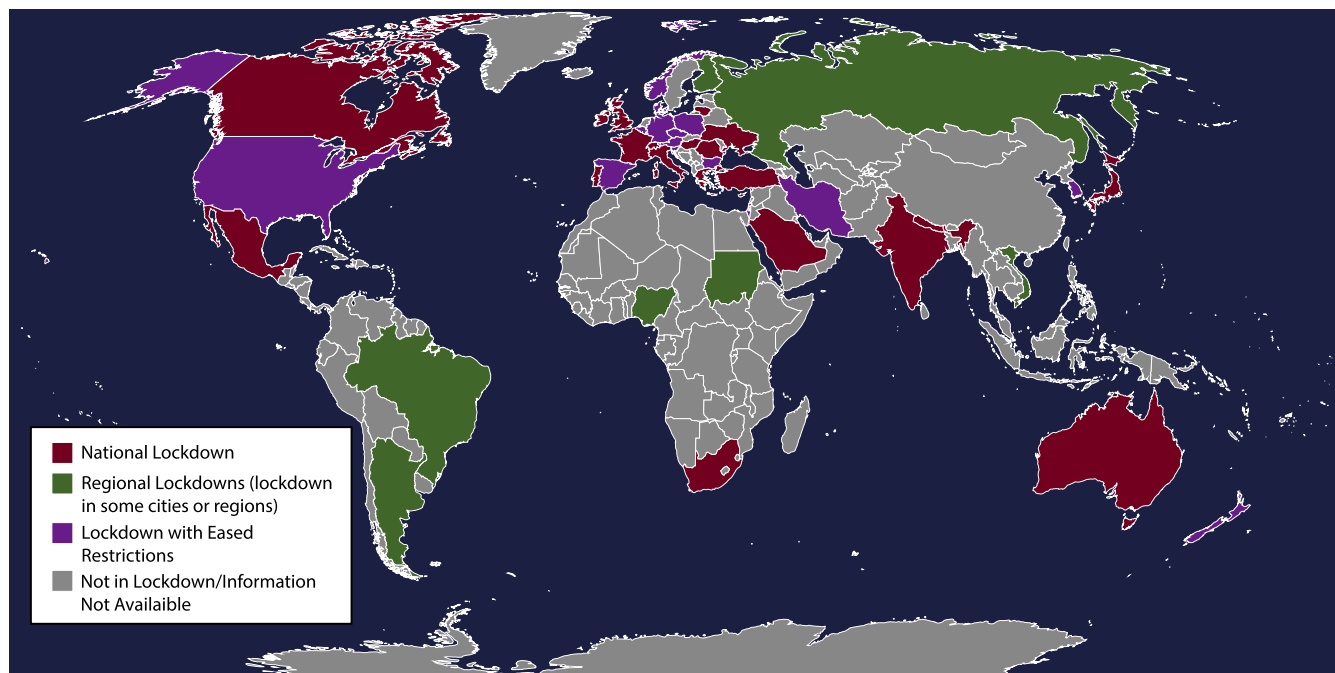


FIGURE 5. Countries in lockdown as of 19 April 2020 (data source: media reports [31]–[48]).

C. STAGE III - CLUSTERS OF CASES

The third stage of the COVID-19 outbreak in a country is marked by the presence of several clusters of COVID-19 cases, i.e., when the disease-causing virus starts circulating within a geographic location and infects individuals who have neither a history of travel nor contact with someone who does. At this stage, it becomes hard to trace the source of the virus transmission, and geographical lockdown becomes highly necessary to prevent the outbreak from reaching stage IV.

D. STAGE IV - COMMUNITY TRANSMISSION

The fourth stage of the COVID-19 pandemic in a country is associated with community transmission, i.e., larger outbreaks of local transmission in a country, leading to an extremely high number of reported incidents and deaths. At this stage, the outbreak gets out of control, and finding a cure or vaccine is the only way to mitigate the impact of the disease. Countries like Iran, Turkey, Canada, and the USA are currently in the fourth stage of the COVID-19 pandemic [29].

V. IMPACT OF THE COVID-19 PANDEMIC ON THE GLOBAL ECONOMY

Owing to the lack of any concrete treatment strategy, social distancing has been identified as the best possible defense strategy against the COVID-19 pandemic at the time of this writing. However, the need for social distancing has prompted governments around the world to impose lockdowns (refer to Fig. 5), which has marked a huge dent in the global economy. All non-essential services have been forced to shut down, causing virtually all the industrial sectors to face significant disruptions in the supply chain (refer to Table 3),

and consequently, putting billions of people at risk of losing their jobs. Furthermore, the rapid outbreak of COVID-19 has forced governments to restrict the trade of a majority of goods across country borders, leaving international trade flows on the verge of collapse. According to the projections put forth by JPMorgan Chase & Co., the COVID-19 pandemic has the potential to paralyze the global economy, with an estimated loss of more than 5.5 trillion US dollars in the next 18-24 months [49]. In this section, we analyze the impact of the COVID-19 pandemic on the overall economy by thoroughly dissecting its impact on different economic sectors.

A. AUTOMOTIVE INDUSTRY

The automotive industry has seen major disruptions in production due to stringent lockdown measures enforced in several countries worldwide as an effort to contain the pandemic. As social distancing is enforced and people are required to stay in their homes, usage of automobiles, including both public & private transport, has declined across the world. The only automobiles currently in use are the vehicles associated with essential services.

1) RELEVANT STATISTICS

- In China, the automobile industry saw an 18% drop in sales in year-over-year (YoY) sales of January 2020. Despite containment efforts, this number escalated to 79.1% in February 2020, which is the biggest ever YoY drop experienced by the Chinese automotive industry [50].
- In March 2020, the YoY sales of passenger vehicles and commercial vehicles in India saw a decline of 52% and

TABLE 3. Industries hit hardest by the COVID-19 pandemic.

Industry	Risk Factors		
Automotive Industry	Sudden drop in sales	Automobile plants shut	Sharp drop in stock prices
Aviation Industry	High cancellation rates	Decreased revenues	Increased debts
Tourism Industry	Decrease in ITRs	Decrease in consumer confidence	High cancellation rates
Oil Industry	Collapse in oil prices	Imbalance in demand & supply	Travel restrictions
Construction Industry	Unavailability of labor	Decline in real estate demand	Financial difficulties
Food Industry	Government guidelines	Instability in food demand & supply	Potential supply chain disruptions
Healthcare Industry	Unprecedented load	Healthworkers at high risk of infection	Lack of resources
Telecommunications Industry	Traffic congestion	Workforce reduction	Network reliability

89%, respectively, as dealers were forced to shut down their showrooms following government stipulations to limit the spread of COVID-19 [51], [52].

- According to the European Automobile Manufacturers Association (ACEA), the combined production losses in the European Union (EU) and the United Kingdom amount to more than 2.1 million vehicles as of 28 April 2020. Additionally, employment of more than 1.1 million people has been adversely affected due to factory shutdowns [53].
- In the USA, the COVID-19 outbreak has forced a majority of automakers, including General Motors, Fiat, Ford, and many others, to suspend their production activities [54]. According to the estimates published by the Alliance for Automotive Innovation on 26 March 2020, 93% of all automobile production plants were forced to close down in the USA following the COVID-19 outbreak [55].

B. AVIATION INDUSTRY

The COVID-19 pandemic has had a massive impact on the aviation industry. Affected countries, which includes almost all the nations, have been forced to impose travel bans on both international and domestic passenger flights. The only active airways include critical supply routes that support cargo and freight aircraft.

1) RELEVANT STATISTICS

- As per a recent report published by the International Air Transport Association (IATA), the global air travel demand increased by just 2.4% in January 2020, which is the lowest YoY increase registered in the last decade [56]. The major disruption in travel demand, however, was recorded between 24 and 30 March 2020, when the reported number of operational flights plummeted to 280,000, a sharp decline from 780,000 flights reported in the same period in 2019 [57].

- According to the most recent IATA estimates, the airline industry is well on track to lose as much as 314 billion US dollars in revenues globally, following the COVID-19 crisis [58].
- As airline services are currently stalled, the demand for the purchase of new aircraft has also dropped. The total number of aircraft orders has decreased from 1858 in 2018 to 235 in 2020 [59].

C. TOURISM INDUSTRY

The tourism industry has been one of the worst affected industries following the outbreak of COVID-19. Revenues generated from the tourism sector account for 10% of the world's GDP. Therefore, any adversity faced by the tourism sector has the potential to dent the global economy severely.

1) RELEVANT STATISTICS

- According to the World Travel & Tourism Council (WTTC) estimations, the COVID-19 pandemic could lead to a layoff of about 50 million people associated with the tourism industry worldwide [60].
- As per the figures issued by the United Nations World Tourism Organisation (UNWTO), international visitor arrivals could fall by up to 30% in 2020, which corresponds to a loss of 300-450 billion US dollars in international tourism receipts (ITRs) [61].

D. OIL INDUSTRY

The shutdown of international and domestic passenger aircraft across the world has resulted in a drastic decline in the consumption of aviation fuel. Similarly, on the ground, all non-essential traffic remains stalled, causing a sharp decline in the global oil demand.

1) RELEVANT STATISTICS

- In China, the demand for crude oil has fallen by around 3 million barrels a day (which corresponds to 20% of the total consumption) [62].

- The Brent crude oil benchmark collapsed over 65% in the first quarter of 2020, while the West Texas Intermediate (WTI) benchmark recorded a drop of more than 66%. With oil prices plummeting to nearly 25 US dollars, both these benchmarks have recorded their worst ever quarter in history [63].

E. CONSTRUCTION INDUSTRY

Construction firms are likely to face severe disruptions and delays in current projects on account of the COVID-19 pandemic. Due to a majority of the workforce being unable to work as a result of stringent self-quarantine guidelines, most construction firms will be required to cease all non-essential operations until the outbreak is contained. This will likely result in the large scale re-scheduling of existing projects, which might lead to severe losses for the industry.

1) RELEVANT STATISTICS

- Within just the first two months of the year, fixed asset investment in China dropped by 30.3%, while the real estate development dropped by 16.3% [64].
- The widespread impact of the COVID-19 outbreak on the construction sector in China and other leading economies has prompted GlobalData³ to update its estimate for construction growth in 2020 from 3.1% to 0.5% [65].

F. FOOD INDUSTRY

In comparison to other sectors, the impact of the COVID-19 pandemic has not been as severe on the food industry. Recognition of food as an essential commodity has allowed supply chains associated with food products to remain operational. In fact, as per the Food and Agriculture Organization (FAO) of the United Nations (UN), packaged food demand has risen significantly in the months following the COVID-19 outbreak [66]. However, that does not go as far as to say that the industry has not been affected at all. While supply chains for essential food items are kept open, restaurants, cafes, and other luxury food service providers have been forced to shut down [67]. Furthermore, several grocery store owners and supermarkets are often finding themselves unable to meet the rising demands owing to ‘panic buying’ and stocking up of food supplies by the masses [68]–[70].

G. HEALTHCARE AND MEDICAL INDUSTRY

The COVID-19 pandemic has had a devastating effect on the healthcare systems across the world. While most industrial sectors have been economically affected due to the inactivity caused as a result of lockdown measures & travel bans, what the healthcare industry is witnessing is far from stagnation. Hospitals across the world are currently facing a shortage of ventilators, intensive care units (ICUs), and personal protective equipment (PPE) required to manage the COVID-19 patients. The healthcare systems of even the most

developed countries in the world are on the brink of collapse due to the exponentially increasing number of COVID-19 patients [71]–[74].

H. TELECOMMUNICATIONS INDUSTRY

The impact of the COVID-19 pandemic on the telecommunications industry has been sporadic. Various telecommunication service providers (TSPs) and internet service providers (ISPs) have reported witnessing a massive increase in traffic [75]. The large scale consumption of network bandwidth has been attributed to the governments’ lockdown efforts, which have forced the educational institutions to use online platforms of teaching, and companies to allow their employees to work from home. However, the COVID-19 pandemic has not left the telecommunications sector unscathed. Much like other industrial companies, a majority of TSPs & ISPs have recorded a massive drop in their share prices over the past few months. In GlobalData’s share price analysis of some of the top TSPs worldwide, it was revealed that share prices of telecom behemoths AT&T, China Telecom, and Telefonica plummeted by more than 20% between 1 January and 25 March 2020 [76].

The large scale implications of the COVID-19 pandemic on the global economy are attributed to the substandard response system adopted following its initial outbreak. Although the response to the COVID-19 pandemic has been more organized than the response to previous epidemics and pandemics, a few issues in the current epidemic/pandemic response system remain. Table 4 lists all the underlying issues with the current response, along with the key learning points for future public health emergency management [10]. These lessons are very relevant not just for other health crises but also in case there is a second/third wave of the COVID-19 pandemic in the future.

VI. DIAGNOSTIC TESTING FOR THE COVID-19

Given the significant spurt in COVID-19 cases across the world in the past few months, a carefully devised strategy for reliable diagnosis is the need of the hour. The onset of stage II and stage III of the COVID-19 outbreak has prompted a majority of the countries worldwide to extend their scope of testing beyond individuals with foreign travel history. However, due to the insufficient number of testing kits, large-scale testing of the COVID-19 is infeasible. Furthermore, the inability to distinguish the symptoms of COVID-19 from the symptoms of common flu has made it difficult for governments across the world to determine fixed criteria required to carry out a test. To this end, the CDC has issued priority-based testing criteria to guide the evaluation of COVID-19 cases. The criteria assign the highest priority to healthcare workers & hospitalized patients showing symptoms of COVID-19 infection, while symptomatic patients a) above the age of 65, or b) having existing medical conditions, have been given the second priority. The entire guidelines for the testing criteria have been listed on the official website of the CDC [77].

³a data analytics and consulting company

TABLE 4. Lessons drawn from the current response to the COVID-19 pandemic [10].

Underlying Issue	Event	Repercussion	Learning Objective
Lack of Transparency	Coercion of researchers who recognized the COVID-19 soon after it came into existence.	Delayed dissemination of knowledge regarding COVID-19 patients.	Establish stringent guidelines ensuring the immediate release of information concerning potential health emergencies.
Delayed Travel Restrictions	Aviation services worked at international frontiers for more than a month after the initial outbreak of the disease with insufficient screening measures.	Infected individuals were able to travel across international borders with ease, thereby exacerbating the outbreak.	Following the outbreak of a disease, precautions, such as health screening measures and travel restrictions should be introduced sooner.
Delayed Lockdown Measures	The epicenter of the COVID-19, Wuhan, established lockdown measures almost a month after the infection's initial identification.	Difficulty in containing the spread of the disease as infected individuals freely transmitted the virus.	Isolate high-risk regions immediately after the identification of a potential health risk.
Public Misinformation	Dissemination of false information, confusion, and conspiracy theories.	Rise of xenophobia and frivolous fears surrounding the COVID-19.	Establish rigid policies for monitoring the spread of inaccurate information.
Announcement Delay	Global public health emergency declared by the WHO almost one month after the initial outbreak.	The potential disastrous implications of the outbreak were not acknowledged.	Proactively monitor the impact of the disease to recognize its threat status promptly.
Cognitive Bias	The initial warnings issued by several scientists about the COVID-19 ignored. Policy measures adopted by various governments met with cynicism.	Deliberate defiance of government orders leading to further spread of the disease.	Individuals should make an effort to overcome their cognitive biases and follow government orders.
Insufficient Stock of PPE	The inability of various governments worldwide to provide their healthcare workers with adequate protective gear.	Several healthcare workers exposed to the disease.	A higher degree of pandemic preparedness is required.

A. CONTACT TRACING

Contact tracing refers to the process of identifying people with a history of exposure to infected individuals. The relatively long incubation period associated with the COVID-19 and the absence of large scale testing has made it extremely challenging for the authorities to identify the actual number of infected patients. This leaves the process of contact tracing as the only viable option. According to the WHO [78], the process of contact tracing involves three steps:

- i) Identifying individuals with a history of contact with an infected person.
- ii) Recording the details of those individuals.
- iii) Getting those individuals tested as soon as possible.

Adopting the process of contact tracing can be particularly advantageous for the countries currently in the first and the second stage of the COVID-19 outbreak.

B. CLINICAL TESTS FOR COVID-19 DETECTION

Developing accurate and reliable tests to diagnose SARS-CoV-2 infection in individuals is essential to curb its rapid transmission. The currently available COVID-19 tests can be broadly classified into two types:

1) MOLECULAR TESTS

The WHO-recommended Nucleic Acid Amplification Test (NAAT) has emerged as the most popular test for detecting an active SARS-CoV-2 infection [79]. These tests involve

the use of the nasopharyngeal swab technique, wherein a sample comprising a mixture of mucus and saliva is obtained from the back of the throat (upper respiratory tract) using a cotton swab (kindly refer to Table 5 for details on other types of sample collection techniques). However, in case the person being tested is suffering from severe respiratory ailments, the WHO recommends obtaining specimens from his/her lower respiratory tract as well [80]. These samples are then brought to a specialized laboratory, where they are assessed for detecting the presence of viral RNA using a real-time Reverse-Transcription Polymerase Chain Reaction (rRT-PCR) test [81]. A diagnosis of the COVID-19 is only confirmed if the test identifies either:

- i) the presence of two discriminatory targets for the SARS-CoV-2 genome, one of which is preferably explicit to the SARS-CoV-2, or
- ii) the presence of betacoronavirus followed by the identification of SARS-CoV-2 using partial or complete sequencing of the virus genome (the target sequence should be larger than the amplicon on which the NAAT assay is used).

The viral genes being targeted by the Nucleic Acid Amplification Tests (NAATs) are the N, E, S, and RdRp genes. Identification of just a single gene in the NAAT generates the need for a repeat test of the patient. In any subsequent tests, the WHO recommends using a different specimen and target sequence from the one used in the initial test [80].

TABLE 5. Various techniques for coronavirus sample collection.

Sample Collection Techniques	Overview
Nasopharyngeal Swab	A special swab is used to take a sample of nasal secretions from the back of the nose or throat.
Nasal Aspirate	Unlike the Nasopharyngeal Swab technique, this method involves the use of a catheter attached to a syringe for obtaining samples from the nasopharynx. Before collecting the sample, a saline solution is injected into the nose of the person being tested [82].
Endotracheal Aspirate (ETA)	It is a diagnostic method of the lower respiratory tract wherein the sample is collected from the lungs using a thin tube known as a bronchoscope [83].
Bronchoalveolar Lavage (BAL)	After the introduction of a sterile saline solution, a fiber-optic bronchoscope is passed through the mouth or nose into the bronchoalveolar tree, and a sample is collected.
Sputum Test	Sputum, also referred to as phlegm, is a thick mucus that is coughed up from the lungs. This test involves collecting the coughed-up sputum in a special cup [84].
Blood test	A blood specimen is taken from a vein in the arm [84].

TABLE 6. COVID-19 candidate vaccines in clinical evaluations.

Candidate Vaccine Type	Trial Title	Phase	Primary Sponsor
Adenovirus Type 5 Vector	A randomized, double-blinded, placebo-controlled phase II clinical trial for Recombinant Novel Coronavirus (2019-nCoV) Vaccine (Adenovirus Vector)	Phase II	Institute of Biotechnology (Academy of Military Medical Sciences)
ChAdOx1	A Study of a Candidate COVID-19 Vaccine (COV001)	Phase I/II	University of Oxford
Inactivated	A randomized, double-blind, placebo parallel-controlled phase I/II clinical trial for inactivated Novel Coronavirus Pneumonia vaccine (Vero cells)	Phase I/II	Wuhan Institute of Biological Products
Inactivated + Alum	Safety and Immunogenicity Study of Inactivated Vaccine for Prophylaxis of SARS CoV-2 Infection (COVID-19)	Phase I/II	Sinovac Research and Development Co., Ltd.
mRNA	Phase I/II Trial Investigating the Safety and Effects of Four BNT162 Vaccines Against COVID-2019	Phase I/II	BioNTech RNA Pharmaceuticals GmbH
DNA plasmid vaccine with electroporation	Safety, Tolerability and Immunogenicity of INO-4800 for COVID-19 in Healthy Volunteers	Phase I	Inovio Pharmaceuticals
LNP encapsulated mRNA	Safety and Immunogenicity Study of 2019-nCoV Vaccine (mRNA-1273) for Prophylaxis SARS CoV-2 Infection (COVID-19)	Phase I	National Institute of Allergy and Infectious Diseases (NIAID)

Source: WHO Draft Landscape of COVID-19 Vaccines - 26 April 2020

While NAATs have high sensitivity (true positive rate) and specificity (true negative rate), one of their drawbacks is that they can only diagnose current cases of infection, i.e., they do not provide any insights as to whether someone had the infection earlier.

2) SEROLOGICAL TESTS

Unlike molecular tests that detect the presence of the virus itself, serological tests are used to detect the existence of antibodies in the bloodstream of the person being tested. Antibodies are proteins formed by the white blood cells to combat a specific antigen. By enabling healthcare experts to identify individuals who have developed an immune response to the infection, serological tests have the potential to play a massive role in the fight against COVID-19 [85]. However, serological tests also have one significant shortcoming. They

do not have the ability to detect a disease during its early days when the body is still building antibodies against the infection.

VII. TREATMENT

COVID-19, caused by the novel SARS-CoV-2, has led the world into an unprecedented state of severe disarray. At the time of writing, no definitive treatment or preventive vaccine exists for the coronavirus. As such, the treatment of COVID-19 is mostly symptomatic, i.e., the type of treatment administered depends on the specific symptoms exhibited by the patient.

Most cases of the coronavirus disease have been classified as mild, with patients recovering on their own without the need for supportive care. Therefore, it is recommended that patients with mild COVID-19 symptoms be managed at home

to avoid placing additional strain on the already stressed-out health systems. However, severe and critical cases of COVID-19 do tend to require hospitalization. Patients experiencing hypoxemia⁴ may require the provision of additional oxygen via face masks or ventilators. Co-infections that occur as a result of a weakened immune system, due to the virus, are treated with necessary antibiotics and antifungals on a case by case basis. As the SARS-CoV-2 virus may affect the kidney as well, renal replacement therapy might be required in some cases [21]. In any case, patients diagnosed with the disease need to be put under strict isolation, irrespective of the severity of the symptoms, in order to prevent further transmission.

While no definitive antiviral medicine or preventive vaccine for SARS-CoV-2 is available to date, various attempts are being made to make one available for commercial use as soon as possible. In the following subsections, we address the efforts being made to produce potent vaccines and drugs for COVID-19 treatment.

A. VACCINE DEVELOPMENT

Developing vaccines for viral diseases is particularly challenging, owing to their capability to mutate from one person to another. Nevertheless, the development of reliable & potent vaccinations is the only viable way of bringing the COVID-19 pandemic to an end. Following the outbreak, various medical organizations, independent laboratories, and scientists have been attempting to create a vaccine for the SARS-CoV-2. According to the WHO, as of 26 April 2020, around 82 candidate vaccines are in the pre-clinical stage, while 7 have already entered the clinical evaluations (refer to Fig. 6) [86]. Some of the most significant efforts being made in the direction of COVID-19 vaccine development are as follows:

1) MODERNA'S mRNA-1273

Moderna, a US-based biotech company, has put forth a vaccine candidate in collaboration with the National Institute of Allergy and Infectious Diseases (NIAID). Moderna's approach is based on the injection of mRNA, a genetic form of the virus' genome, into human cells to allow them to generate proteins required to combat the virus. Unlike the methods adopted in conventional vaccines, this approach does not require growing large numbers of the virus [87]. Although this vaccine has entered the first phase of clinical trials on 15 March 2020, its commercial release is expected to be more than a year away [88].

2) CanSino's Ad5-nCoV

Another candidate vaccine that is undergoing clinical evaluations is the adenovirus type-5 vector-based recombinant COVID-19 vaccine (Ad5-nCoV). Developed by CanSino Biological Inc in association with the Beijing Institute of Technology (BIT), Ad5-nCoV uses the non-replicating viral

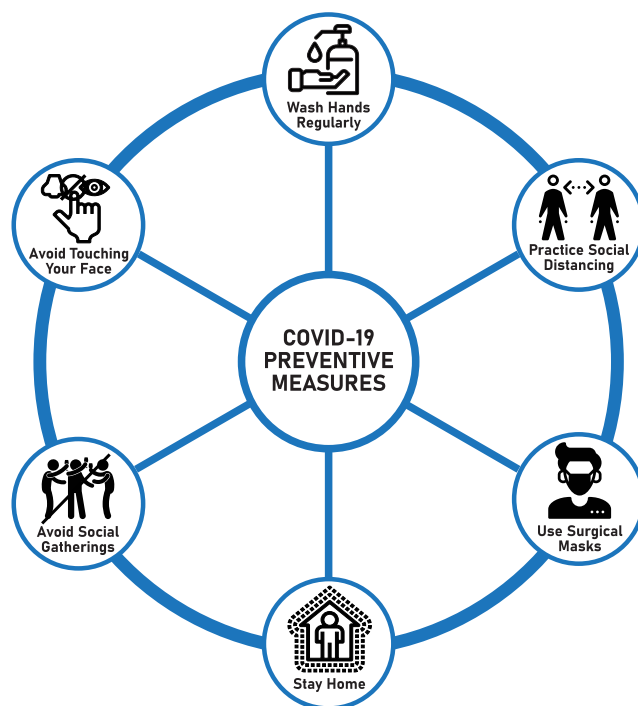


FIGURE 6. COVID-19 preventive measures.

vector as its platform, the same as the one used in their Ad5-EBOV vaccine for Ebola. This vaccine relies on the adenovirus type-5 vector to stimulate immune responses that work against the disease. Given the positive response recorded in the first phase of clinical trials, CanSino might move for an expedited phase II clinical trial [89].

3) PittCoVacc (PITTSBURGH CORONAVIRUS VACCINE)

The researchers at the University of Pittsburgh School of Medicine have recently developed a vaccine against the SARS-CoV-2 named PittCoVacc [90]. Unlike the mRNA vaccine candidate developed by Moderna, PittCoVacc adopts the more conventional method of building immunity using laboratory-generated pieces of viral protein. The preliminary tests conducted on mice revealed that PittCoVacc triggered the development of a large number of antibodies against SARS-CoV-2 within two weeks of it being administered. Pending FDA's approval, phase I of the clinical trials for this vaccine are slated to commence soon [91].

4) JOHNSON & JOHNSON'S COVID-19 LEAD VACCINE

Healthcare conglomerate Johnson & Johnson, and the Biomedical Advanced Research and Development Authority (BARDA), a subdivision of the US Department of Health and Human Services (HSS), have pledged to collectively invest more than 1 billion US dollars in the R&D of COVID-19 vaccines. On 30 March 2020, Johnson & Johnson declared that it had identified its lead candidate vaccine after three months of comprehensive research on several vaccine candidates in collaboration with the Beth Israel Deaconess Medical Center,

⁴a low level of arterial oxygen supply

TABLE 7. Promising candidate drugs for the treatment of COVID-19.

Candidate Drug	Trial Title (Acronym)	Phase	Primary Sponsor
Arbidol	Clinical Study of Arbidol Hydrochloride Tablets in the Treatment of Pneumonia Caused by Novel Coronavirus	Phase IV	Jieming QU
Hydroxychloroquine with Azithromycin	Azithromycin in Hospitalized COVID-19 Patients (AIC)	Phase IV	Shahid Beheshti University of Medical Sciences
Favipiravir	Favipiravir in Hospitalized COVID-19 Patients (FIC)	Phase IV	Shahid Beheshti University of Medical Sciences
Bromhexine with Hydroxychloroquine	Use of Bromhexine and Hydroxychloroquine for Treatment of COVID-19 Pneumonia	Phase IV	General and Teaching Hospital Celje
Remdesivir	Study to Evaluate the Safety and Antiviral Activity of Remdesivir (GS-5734™) in Participants With Severe Coronavirus Disease (COVID-19)	Phase III	Gilead Sciences
Lopinavir/Ritonavir	Effectiveness and Safety of Medical Treatment for SARS-CoV-2 (COVID-19) in Colombia	Phase III	Universidad Nacional de Colombia
Tocilizumab	Efficacy of Tocilizumab on Patients With COVID-19	Phase III	Massachusetts General Hospital
RhACE2 APN01	Recombinant Human Angiotensin-converting Enzyme 2 (rhACE2) as a Treatment for Patients With COVID-19 (APN01-COVID-19)	Phase II	Apeiron Biologics

Source: U.S National Library of Medicine (Trial Phases as on 29 April 2020)

a division of the Harvard Medical School. Johnson & Johnson plans to launch the clinical trials of its lead candidate vaccine by September 2020 at the latest [92].

5) MULTIPLE EFFORTS MADE BY THE CEPI

The Coalition for Epidemic Preparedness Innovations (CEPI), a Norway-based foundation established to expedite the development of vaccines against emerging infectious diseases, has initiated collaborations with several organizations & institutes across the world to aid in the development of effective vaccines against the SARS-CoV-2. CEPI and GlaxoSmithKline (GSK) announced a new partnership on 3 February 2020, which will see GSK make its existing adjuvant technology available to the CEPI [93]. On 11 February 2020, CEPI struck a partnership with the International Vaccine Institute (IVI), an international organization based in the Republic of Korea, which shares its vision of a COVID-19 free world. Under the terms of this partnership, the IVI will render its technical expertise in the CEPI-sponsored projects in exchange for which it will receive funding from the CEPI [94]. In addition to the partnership efforts, the CEPI has pledged initial funding to various institutes, including the University of Queensland, University of Hong Kong (HKU), University of Oxford, and the Pasteur Institute, to accelerate the development of effective vaccines against SARS-CoV-2. To date, the CEPI has invested a sum of 29.2 million US dollars in the R&D of various COVID-19 vaccines [95].

Although researchers around the world are making determined attempts to come up with a vaccine for the extirpation of the COVID-19, the imminent arrival of an effective vaccine seems implausible. Two main reasons for the same are mentioned below:

- i) In the last two coronavirus outbreaks, namely SARS and MERS, it was observed that once the vaccine was administered to an individual, there was a sudden

increase in his/her immune response (cytokine bursts). Cytokine bursts often lead to acute respiratory distress syndrome (ARDS), which is considered to be the leading cause of death in COVID-19 patients. To avoid such complications and to ensure that the vaccines currently in development do not prove to be counter-effective later, it is necessary to certify that these vaccines have a good safety profile.

- ii) Sometimes, a single dose of vaccine is not sufficient to develop sufficient antibodies. For example, the Hepatitis B vaccine is given in 3 doses, each of them months apart. Once identified, the need for wide-scale production of the COVID-19 vaccine to meet world requirements is anticipated to take much time. Adding to that, if multiple doses across several months are required, it will take an even longer time before we can rely on vaccines for bringing the COVID-19 pandemic to an end.

B. POTENTIAL DRUGS FOR TREATMENT

Many pharmaceutical companies have come up with potential drugs as solutions to treat the coronavirus disease. While no drug is globally approved as of yet, several of these drugs are being tried out, with some of them in various phases of clinical trials (refer to Table 7). As of 29 April 2020, more than 1800 clinical trials worldwide are listed on the WHO's International Clinical Trials Registry Platform (ICTRP) [96]. Among the drugs being tested, Remdesivir, Hydroxychloroquine, and Arbidol have shown immense promise, and are already undergoing clinical trials at several hospitals across the world [97], [98]. Earlier in 2008, Arbidol was shown to have promising results against the pathogens of the SARS-CoV virus in cellular models [99]. It was also proven to be effective against influenza type A and B viruses, as well as the Hepatitis type C virus [100].

Another drug that has emerged as a candidate to treat the COVID-19 is the Shuang-Huang-Lian (SHL), a well known traditional Chinese drug used to treat various bacterial and viral infections. Chinese Researchers have reported that SHL oral liquid may have inhibitory properties against the SARS-CoV-2 virus due to the presence of baicalin, chlorogenic acid, and forsythin, which are known to have inhibitory effects against multiple pathogenic viruses [101], [102]. It is important to note, however, that currently there is no conclusive evidence backing the use of SHL oral liquid as a treatment for the COVID-19.

Although various attempts are being made to develop efficient treatment strategies against the COVID-19, a commercially viable vaccine might not be possible for at least another year. Therefore, the best way to keep the disease from spreading any further is to limit the exposure of non-infected individuals to infected individuals. In the following section, we discuss the various preventive measures suggested by the WHO and the CDC against the COVID-19 [103], [104].

VIII. PREVENTIVE MEASURES

As the world continues to suffer from the COVID-19 health crisis, it is essential to follow effective preventive measures (Fig. 6) to minimize the likelihood of becoming another casualty. If individuals and communities comply with the practices mentioned below, the world may soon witness a flattened COVID-19 curve. Flattening the curve implies bringing down the spread of the COVID-19 to the extent where available healthcare facilities can sufficiently handle the impact of the disease.

- i) Clean your hands frequently with an alcohol-based hand sanitizer or wash them thoroughly with soap and water.
- ii) Practice social distancing - Seek to keep yourself at a distance of at least 1 meter (3 feet) from others.
- iii) Stay at home unless absolutely necessary to go out. Individuals above 60, people with underlying health conditions, and pregnant women are especially advised to stay away from all social interactions.
- iv) Avoid touching your eyes, nose, and mouth without thoroughly cleansing your hands.
- v) Frequently touched surfaces, such as doorknobs, desks, phones, light switches, and laptops should be routinely disinfected.
- vi) Cover your coughs & sneezes with a cloth, handkerchief, or a tissue. If none of these are readily available, coughing/sneezing into your elbow pit is advisable.
- vii) It is advisable to wear masks around other people. However, care should be taken to ensure their proper disposal [105].

The rapid outbreak of the COVID-19 has placed sincere emphasis on the need to follow good practices in daily life, like washing hands, taking regular baths, improving eating habits, and much more. It is important to note that good hygiene practices and eating habits should be followed, not just during the COVID-19 pandemic, but also after it.

IX. EMERGING TECHNOLOGIES FOR MITIGATING THE IMPACT OF THE COVID-19 PANDEMIC

As the novel coronavirus continues its onslaught across the globe, the world is reeling under the weight of crashing economies and piling casualties. Unfortunately, billions of people are still under a constant threat of infection, with the situation not likely to get any better in the coming days. However, a multitude of technological approaches are emerging to deal with the impacts of the COVID-19 pandemic. Among them, digital technologies, including IoT, AI, blockchain, and next-generation telecommunication networks like 5G, have been at the forefront [106]. According to the WHO and the CDC, digital technologies can play an essential role in improving public health response to the COVID-19 pandemic [107]. In the following sections, we explore the efficacy of the aforementioned technologies in allaying the disastrous impacts of the COVID-19 pandemic.

X. IoT & IoMT

The Internet of Medical Things (IoMT), also referred to as the healthcare IoT, is an amalgamation of medical devices and software applications offering extensive healthcare services, that are connected to the healthcare IT systems (refer to Fig. 7). In recent times, much like the IoT, IoMT has witnessed a surge in the number of its potential applications [108]. This surge is attributed to the fact that an increasing number of mobile devices are now equipped with Near Field Communication (NFC) readers that allow these devices to interact with IT systems [109]. Applications of IoMT include 1) monitoring patients from a remote location, 2) tracking medication orders, and 3) using wearables to transmit health information to the concerned health care professionals.

Owing to their ability to collect, analyze, and transmit health data efficiently, the health care sector has realized the transformative potential of IoMT technologies [110], [111]. Amid the ongoing COVID-19 pandemic, several innovators, medical organizations, and government bodies are looking to leverage IoMT tools in order to reduce the burden on the healthcare systems. In the following few sections, we explore various IoT & IoMT technologies that have made a sizable contribution in monitoring, and consequently, managing the impact of the COVID-19 pandemic.

A. SMART THERMOMETERS

Eight years ago, a US health technology company named Kinsa had launched internet-connected thermometers to screen people for high fevers. Although these thermometers were initially developed to track the common flu, they are, nevertheless, proving to be highly useful in identifying the potential COVID-19 clusters throughout the USA. Following the COVID-19 outbreak, Kinsa Health has deployed more than a million smart thermometers to households in various cities of the USA. These thermometers are linked to a mobile application, which allows them to transmit their readings to the company immediately. Once received, this data is

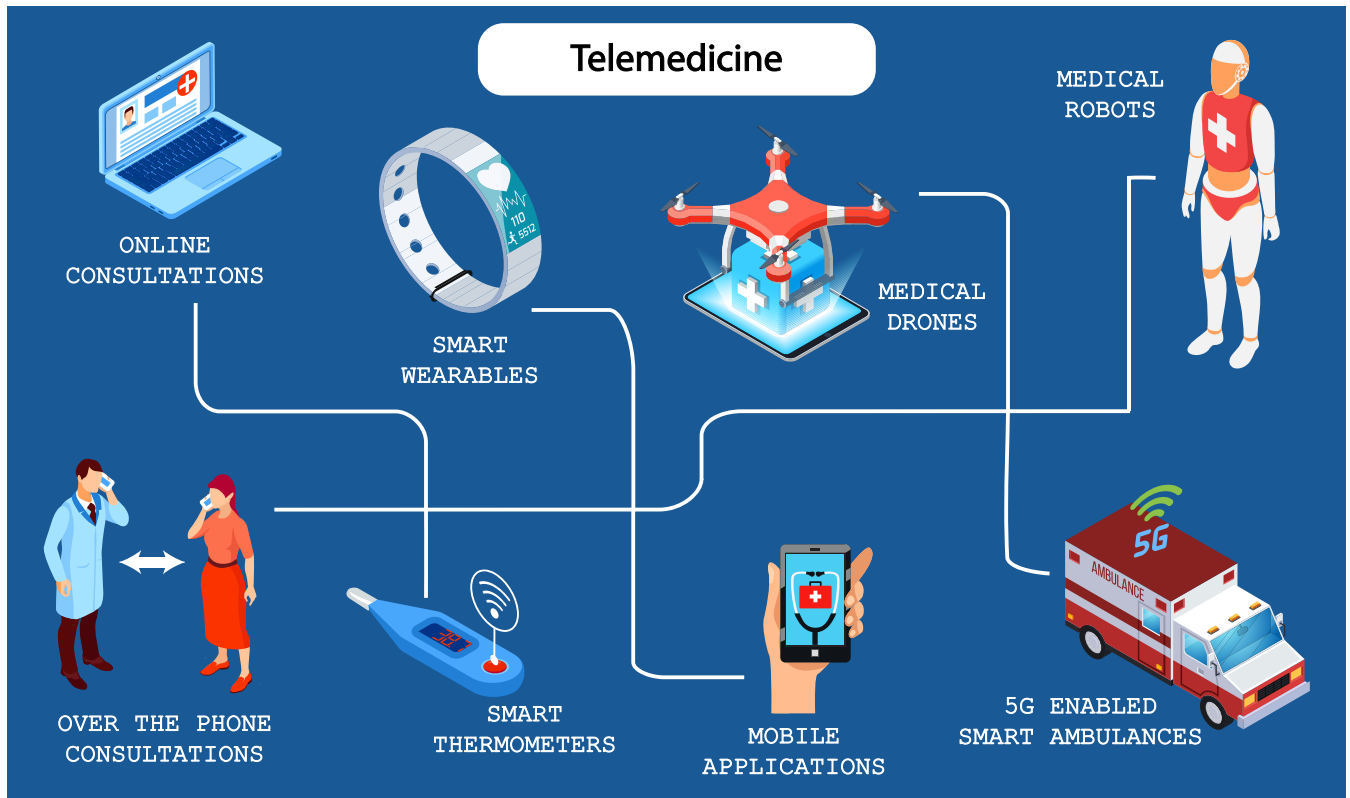


FIGURE 8. Various technologies enabling telemedicine.

advantages. Not only can they ensure minimized human interaction, but they can also be used to reach otherwise inaccessible areas. China, the first country to face the wrath of the COVID-19, has made great use of drone technology to counter the COVID-19 outbreak. Taking that as inspiration, several countries around the world have joined forces with numerous researchers and innovators in an attempt to find ingenious ways of using drones to fight the COVID-19 (refer to Fig. 9). In this section, we explore the numerous benefits that drones can provide in terms of managing the COVID-19 pandemic or any other future outbreak.

A. CROWD SURVEILLANCE

To contain the spread of the COVID-19, governments around the world are taking all the necessary steps to ensure social distancing. To this end, many countries around the world, including China and India, have adopted the drone technology for crowd surveillance.

MicroMultiCopter, a leading industrial drone manufacturer based out of Shenzhen in China, has deployed over 100 drones in several cities of China in an attempt to survey areas and observe crowds efficiently [125]. The drones, equipped with sky speakers, can also be used to give instructions to people not in compliance with the guidelines issued by the Chinese government.

In India, a global technology solutions company named Cyient has provided the Telangana police with unmanned aerial spectrum monitoring technology to help manage the

COVID-19 lockdown. The drones deployed are equipped with surveillance cameras that can effectively monitor sensitive areas in the city and allow the police to handle any unwarranted situation promptly [126].

B. PUBLIC ANNOUNCEMENTS

In addition to crowd surveillance, drones can prove to be highly useful for broadcasting important information, particularly in areas that lack open channels for communication. The police authority in Madrid, Spain, used a drone equipped with a loudspeaker to inform people of the guidelines put in place regarding the state of emergency that was imposed [127]. Additionally, several other European countries have regularly used drones to make public announcements exploring people to practice social distancing norms and taking other necessary precautions to limit the spread of the disease [128].

C. SCREENING MASSES

Following the outbreak of the COVID-19, several authorities in China committed themselves to detect COVID-19 patients as soon as possible. They employed the use of drones equipped with infrared cameras to carry out large-scale temperature measurements in several residential areas [128].

In India, the authorities in New Delhi have employed the use of a multipurpose drone to contain the spread of the COVID-19. Dubbed the “corona combat” drone, it is equipped with a thermal camera for screening individuals,



FIGURE 9. UAVs for COVID-19 impact management.

a night vision camera for monitoring the crowd, a portable medical box for carrying essential medical supplies, a loud-speaker for making announcements, and a disinfectant tank with a capacity of 10 liters for sanitizing public spaces [129]. Unlike the infrared thermometers that can measure the temperature of one person at a time, this drone can be used to measure the temperature of multiple people simultaneously [130].

In addition to these efforts, researchers at the University of South Australia, in association with the Canada-based commercial UAV manufacturer DraganFly, are in the process of developing a “pandemic drone” to remotely observe and identify people with infectious respiratory infirmities. These drones are to be installed with a specialized sensor and computer vision system that can monitor people’s temperature and heart rates [131]. These drones are also expected to have the ability to detect people sneezing and coughing in public spaces. If successful, these drones have the potential to revolutionize COVID-19 diagnostics by early detection of potential COVID-19 patients.

D. SPRAYING DISINFECTANTS

In the face of the COVID-19 pandemic, drones can be used to enter contaminated regions and spray disinfectants. This

can minimize the risk of further spread of the disease while also reducing the exposure of frontline workers to the virus. While China and India have routinely used drones for this practice since the onset of the COVID-19 outbreak, Spain has become the first European country to deploy drones for pandemic management. The Spanish military has recently adopted the use of agricultural drones made by DJI, a leading Chinese drone manufacturer, to spray disinfecting chemicals over public spaces [132]. As per DJI’s claims, the drones have a load capacity of 16 liters and can disinfect one-tenth of a kilometer in an hour [128].

E. DELIVERY OF MEDICAL SUPPLIES AND OTHER ESSENTIALS

In September 2019, researchers from the National University of Ireland (NUI) were able to use a UAV to deliver diabetes medication from Galway to a remote location in the Aran Islands. This was the first successful Beyond Visual Line of Sight (BVLOS) diabetes drone mission, and it showed the world how drones have the capability to carry medical supplies reliably [133]. In the current state of crisis, this functionality can prove to be particularly valuable to reduce the burden on the hospitals and health care staff. Drones can be used for the rapid delivery of medicines and supplies 1) from

one medical facility to another or, 2) from medical centers to the COVID-19 patients being cared for in their homes (in case of a mild form of the COVID-19) [134]. An example of the former was seen in China when a drone was used to move medical supplies from the disease control center in Xinchang County to the People's Hospital in Xinchang County without exposing humans to infection [135].

Marut Drones, a Hyderabad-based startup led by a team of Indian Institute of Technology (IIT) alumni, recently launched an entire line of drones to combat the COVID-19 pandemic in India. The company has drones for sanitizing, medicine delivery, thermal analysis, movement monitoring, and crowd surveillance in its arsenal of drones to combat the COVID-19 pandemic. The company claims that their medical delivery drones, equipped with obstacle avoidance and advanced navigation technology, can cover a distance of 12 kilometers in merely 8 minutes, thereby ensuring medical deliveries 80 times faster than the conventional methods [136]. Marut Drones has already offered a few drones to various authorities in Telangana to monitor crowds and disinfect public places [137], [138]. As per the company's estimates, their disinfectant drones have already disinfected areas covering more than 1900 km [136]. Pending approval from the Government of India (GoI), the company also hopes to deploy its delivery drones soon [137].

In the USA, following the devastating impact of the COVID-19, various steps are being taken by different US bodies to introduce drone technology in the country. The Small UAV Coalition has filed a petition for expedited Federal Aviation Administration (FAA) approvals to allow the use of drones for delivering medical supplies. Furthermore, Zipline, a medical product delivery company, is planning to establish an active medical supply delivery network. By delivering urgent medication directly to people's doorsteps, Zipline hopes to reduce the burden on delivery personnel while also promoting the practice of social distancing among people [134].

Apart from being a safe way for delivery of medical supplies, drones can facilitate the delivery of groceries, as witnessed in some parts of Australia, China, and the USA [128]. In China, the e-commerce giant JD.com has started using a few of its drones to make last-mile deliveries of essential goods [139]. Meanwhile, in the USA, Google's parent company - Alphabet, has recorded a considerable increase in the number of deliveries made using its autonomous drone delivery services known as Wing.

F. CHALLENGES

Despite the numerous benefits that UAVs can provide in response to health crises like the COVID-19 pandemic, the use of drone technology is confronted by certain challenges and limitations.

- 1) The integration of UAVs in the COVID-19 impact response system in many countries is limited by the lack of clear government regulatory policies.

- 2) Vulnerabilities in drone operations, such as GPS-jamming and hacking, make drones an attractive prospect for malicious users to conduct cyberterrorism and other unlawful activities. In recent times, many law-enforcement agencies have voiced their concerns about the security risks posed by drones.
- 3) Although considerable strides have been made in the advancement of drone technology in recent years, Beyond Visible Line of Sight (BVLOS) drone operations remain somewhat unsafe. There is a growing need for technological and operational guidelines to warrant the safe operations of UAVs, and consequently, to reap their comprehensive societal benefits.
- 4) At present, UAVs face several constraints in terms of battery life and load capacity, which inhibits their capability to cover long distances and make multiple deliveries at once.

While a few challenges plague the wide-scale use of drone technology, the great promise that it holds in regards to healthcare support cannot be overlooked. Even then, many countries have not yet adopted the use of UAVs in the fight against the COVID-19 pandemic. To this end, government authorities should carefully collect and assess data in regards to existing UAV projects and put more effort into UAV research and development.

XII. ROBOTS & AUTONOMOUS VEHICLES

Much like drone technology, other autonomous technologies like robots and autonomous vehicles (AVs) have made great strides in the fight against the COVID-19 pandemic. In this section, we discuss how authorities around the world have employed the use of these autonomous technologies to mitigate the impact of the COVID-19 pandemic.

A. ROBOTS

As governments and medical organizations around the world struggle to contain the spread of the COVID-19, robots are being deployed to assist in the treatment of patients, and consequently, alleviating the stress levels of the healthcare workers. Additionally, robot-controlled noncontact ultraviolet (UV) surface disinfection methods are also being employed to limit the transfer of the disease via contaminated surfaces. Compared to the practice of manual decontamination, which involves the deployment of cleaning staff and subsequently puts them at risk of contracting the virus, autonomous disinfection robots ensure rapid and effective disinfection of the premises, with little to no human contact [140]. Presented below are a few examples of how robots are being used in hospitals around the world to aid in COVID-19 impact management.

- In India, a Kerala-based startup named Asimov Robotics has developed a three-wheeled robot that can be used to assist patients residing in isolation wards. The robot is capable of doing tasks like serving food to the patients as well as giving them medication, thereby reducing some

burden on the healthcare workers, and freeing them from the risk of contracting the infection.

- Xenex Disinfection Services, a company established by two John Hopkins educated epidemiologists, has developed an autonomous disinfection robot to help limit the number of hospital-acquired infections (HAIs). Xenex asserts that their UV LightStrike Germ-Zapping robots have the potential to efficiently obliterate all types of germs, including various types of viruses and bacteria [141]. Xenex has reported witnessing an enormous surge in demand for its UV Germ-Zapping robot, especially from countries like Singapore, Japan, South Korea, and Italy.
- A Danish robotics company, UVD Robots, has developed multiple disinfection robots to be delivered in hospitals around the world. To date, UVD Robots has delivered its robots to several provinces in China, several parts of Asia, and healthcare markets in Europe and the United States. These robots emit powerful UV light that can disinfect surfaces by tearing apart strands of virus' DNA. The Danish company claims that their robots can operate for about 2.5 hours and disinfect about nine or ten rooms on a single charge [142].

According to a leading robotics expert from the Carnegie Mellon University (CMU), in addition to the tasks mentioned above, robots with the potential to execute tasks like obtaining nasal samples for testing, and rendering support to isolated patients, may also be developed soon [143].

B. AUTONOMOUS VEHICLES

Amid the global health crisis that is the COVID-19 pandemic, AVs could help ease the stress on existing delivery mechanisms while mitigating the risk of virus transmission [144]. China has led the charge in the use of autonomous vehicles (AVs) against the pandemic. In fact, at the time of writing, it is believed to be the only country in the world to deploy AVs for COVID-19 impact management. Beijing-headquartered White Rhino Auto company, in alliance with UNIDO's Investment and Technology Promotion Office (ITPO), dispatched two autonomous delivery vehicles from Beijing to the Guanggu Field Hospital in the Hubei province of China. These vehicles have proved to be highly useful for a variety of tasks, such as delivering medical supplies and meals. The use of AVs not only lessened the workload on the overburdened hospital staff, but it also helped in limiting the risk of cross-infection [145].

XIII. WEARABLES

Wearables are communication enhancing devices worn on the body that are connected to an internet source. Wearables range from smartwatches like Apple Watch, fitness trackers like Fitbit, smart headbands like Dreem, to personal sensors & patches. The ability to monitor people's physical health, along with their stress levels, has made wearables an ideal technology for adoption in the healthcare sector. In the midst

of the current health crisis, various organizations have modified their existing offerings or rolled out new wearables to aid in COVID-19 impact management. Some of these technologies have been discussed below:

A. WHOOP STRAP 3.0

A Boston-based human performance technology start-up, WHOOP, has collaborated with a team of researchers at the Central Queensland University (CQUniversity) in Australia to examine a potential link between alterations in respiratory rates and the COVID-19 symptoms. The primary objective of this study is to be able to develop a mechanism that can identify the COVID-19, well during its incubation period, by detecting early signs of abnormal respiratory behavior in COVID-19 patients. With a high reproductive number, a factor that has made the COVID-19 outbreak so severe, this sort of an early-warning system can help slow the global proliferation of the COVID-19.

In association with the Cleveland Clinic, the researchers at CQUniversity's Appleton Institute plan to carry out a study using 24/7 physiological data, gathered via the wrist-mounted WHOOP Strap 3.0, from hundreds of WHOOP members who have identified themselves as having the COVID-19 and volunteered to be a part of the study [146]. By discerning any deviation in respiratory rates of an individual from their established baseline, the strap can notify that individual of any issues that they might experience. This study will also collect data from the WHOOP Journal, a recently launched online interface accessible from the members' smartphones that enables them to monitor their daily behavior and make healthier lifestyle choices.

Although a few watches from Garmin and Fitbit also have the functionality to measure respiratory rates [146], WHOOP claims to be the only wearable to have its accuracy of measuring cardiorespiratory variables validated by a third-party study [147].

B. ESTIMATE WORKPLACE LEVEL CONTACT TRACING WEARABLE

Estimate, a start-up known for its Bluetooth location beacons, has recently developed a set of wearable devices to enable contact tracing at the workplace, in an attempt to provide employees with a safer workplace environment. This wearable device allows organization leaders to monitor the health status of their employees remotely and to keep a record of any case of COVID-19 transmission amongst them. It empowers an organization's leaders to curb the disease spread before it spreads rampantly within the organization or even outside it [148]. When this device is turned on, it scans for other wearable devices and records any close interactions with them. The devices' hardware includes a passive GPS location-tracker in addition to Bluetooth powered proximity sensors, ultra-wideband connectivity, built-in LTE, and a rechargeable battery [149]. Furthermore, every device has LED indicators and buttons, just like a smartwatch. The purpose of these buttons is to allow the employees to log

their real-time health status. For example, the wearer can update his/her health status as certified healthy, symptomatic, or verified infected. When the wearer updates his/her health status, it is recorded in a central database that stores the information for up to six weeks. There are three variants of these devices: a pebble-like device to be worn around the neck, a wrist-worn version, and a device in the form of a card.

C. LifeSignals BIOSENSOR PATCH

A Silicon Valley start-up named LifeSignals plans to launch a novel biosensor patch that leverages the cardiovascular monitoring technique to assist early detection of the COVID-19 in an individual. This single-use, showerproof, and lightweight wearable named Biosensor Patch1AX, when affixed on the chest area, can record the temperature of the person along with his/her respiration rate, ECG trace, and even the heart rate in real-time. This data is automatically sent from the user's patch to an application on the user's smartphone, enabling them to view their data in real-time [150]. In case a person using this patch develops COVID-19 symptoms, his/her data can also be sent to a centralized and secure cloud platform, alerting the healthcare workers of a potential COVID-19 patient [151]. The patches have been designed in such a way that it can be worn by an individual for five days in one go, post which they can be safely disposed to ensure that the disease does not spread from the patch.

LifeSignals also plans to launch the second version of the patch, Biosensor Patch 2A, in June. By storing and streaming clinical-grade vital signs of a patient, the patch will enable the healthcare workers to monitor COVID-19 patients admitted to the intensive care units (ICUs) [151].

D. SPRY HEALTH'S LOOP SIGNAL

Spry Health is a company that is known for its health management and telemedicine technologies. This company has launched a wearable device called Loop Signal to limit patients from visiting hospitals unnecessarily, especially during such times. Loop Signal helps healthcare personnel to remotely manage the health of people who have symptoms of COVID-19. Worn on the wrist, Loop Signal tracks the heart rate, respiratory rate, and pulse-oximetry of the patient. All these parameters are critical to assess the severity of the COVID-19 in a patient, and can, therefore, empower healthcare professionals to make an in-person visit only if the patient's condition warrants it. This easy-to-wear device helps in collecting hundreds of data points for a patient on a daily basis. The aggregation of a large number of data points provides a much-needed certainty about the present condition of a patient, as opposed to a single data point that may even be an error, sometimes leading to false alarms [152].

E. SPHCC WITH CASSIA AND VIVALNK

Shanghai Public Health Clinical Centre (SPHCC) has employed the use of Bluetooth IoT gateways developed by Cassi Network, and wearable sensors developed by VivaLNK, to monitor COVID-19 patients with minimal

human contact. China has been successful in reducing the count of COVID-19 thanks to the advent of such technologies. In the mechanism put in place by the SPHCC, VivaLNK's wearable sensors constantly supply real-time data about the changes in the body temperature of the patient. Cassia's gateways then collate this data and transmit it wirelessly to the healthcare staff's station. This enables first-line healthcare workers to keep track of their patients' health without having to visit them personally. The Cassia IoT gateways allow nearly 40 Bluetooth Low Energy (BLE) devices to be paired at the same time, thereby facilitating connectivity between multiple rooms of the SPHCC. The use of these technologies in the SPHCC has significantly reduced the healthcare workers' risk of exposure to the infection while also ensuring reduced workload [153].

F. CHALLENGES

Although wearables have played a significant role in the fight against the COVID-19 pandemic, it is essential to note that certain challenges/limitations hinder the use of wearables amid the current health crisis.

- 1) Due to lockdowns and interrupted supply chains, delivery of these wearables is challenging in many parts of the world.
- 2) The battery life of smart wearables is usually in question. The tedious task of charging wearable devices again and again, often dissuades users from buying these devices altogether.
- 3) There are no established guidelines about the use of the private data accumulated using these wearables, which gives rise to a multitude of security and privacy concerns. It is necessary to ensure that the development of such wearables is done while keeping in mind the security and privacy preservation of the users [154].

XIV. MOBILE APPLICATIONS & OTHER PLATFORMS

The use of mobile applications (commonly referred to as apps) has emerged as a prominent strategy in the fight against the COVID-19. Several governments and private organizations around the world have already developed certain apps and platforms for COVID-19 impact management, while several others are in the process of doing so. Most of these modern platforms use a wide variety of technologies, including Bluetooth, Global Positioning System (GPS), and Geographic Information System (GIS). Certain apps have also adopted the use of blockchain, an emerging technology that helps in storing data in the form of immutable blocks. Table 10 lists the key technologies being used to develop contact tracing applications [155]. In this section, we discuss a few of the numerous applications that have emerged in the last few months for combating the COVID-19 crisis.

A. BLOCKCHAIN

A blockchain is a continuously expanding record of transactions between two parties [156]. Such records can be used

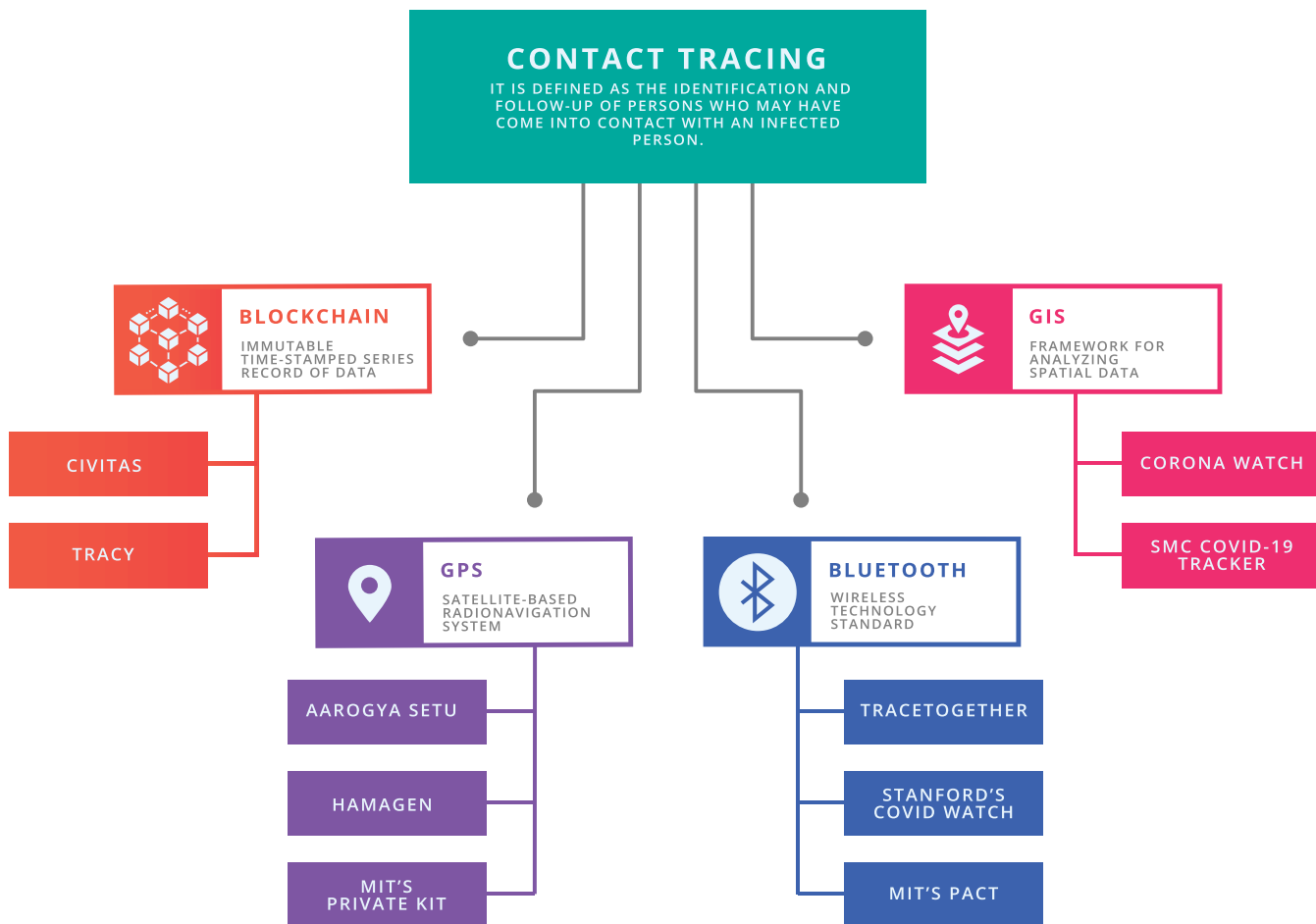


FIGURE 10. Contact tracing applications for COVID-19.

to verify the claims of a party that a transaction has indeed happened. Blockchain is gaining more and more prominence each day thanks to its wide applications in various walks of life [157]. Seeing its utility, numerous companies and authorities across the globe have started using blockchain to build apps that can help in countering the COVID-19. These apps aim to address a crucial problem, which is the lack of integration of verified data sources. According to experts, one of the main advantages of using blockchain-enabled apps is blockchain’s capability of validating continuously changing data. This feature can prove to be quite valuable in managing the rapidly escalating COVID-19 situation. Discussed below are two blockchain-based applications, developed in an attempt to help fight the COVID-19 pandemic:

1) CIVITAS

A Canadian start-up specializing in blockchain solutions has recently launched a safety system, in the form of an app, known as Civitas, that may assist local authorities in various nations of the world to control the impact of the COVID-19. This app associates people’s official IDs with blockchain records to verify whether the person has permission to leave their homes or not. This app also determines the ideal time

and day for people exhibiting the COVID-19 symptoms to go out and buy essential items, thereby minimizing the risk of infecting others. Additionally, Civitas offers a built-in telemedicine functionality that allows doctors to keep track of their patients’ symptoms and send them notes in regards to the medicines to be used and healthcare strategies to be followed. As per the company’s claims, the app makes sure that people’s data remains private and secure [158].

2) MiPasa

MiPasa is a data streaming platform built on top of the Hyperledger Fabric. This platform also draws on the services provided by the IBM blockchain & the IBM cloud platforms, to facilitate the sharing of verified health and location information among individuals, authorities, and hospitals. This application works by collecting the information provided by various medical organizations, public health officials, and other individuals. The WHO recently acknowledged this app to be an effective platform for helping the doctors gain access to verifiable information. The data available on this platform can help the hospitals to determine their future action plans and to efficiently allocate their resources to alleviate the impact of the COVID-19 outbreak [159].

B. GEOGRAPHIC INFORMATION SYSTEM (GIS)

Understanding the geography of the spread of the COVID-19 is crucial to comprehend the severity of the crisis in a particular region, and to deploy appropriate measures to mitigate the impact of the disease in that region. To this end, the GIS systems use spatial analytics, mapping, and location intelligence to map the occurrence of the diseases against multiple parameters such as demographics, environment, and past occurrences. This kind of data will help 1) epidemiologists to understand the origins of the outbreak and, 2) governments to identify high-risk areas and deploy healthcare facilities accordingly.

1) ESRI ArcGIS APPLICATION

California-based Environment Systems Research Institute (Esri) is an international provider of GIS software, whose product line includes ArcGIS Desktop, ArcGIS Pro, ArcGIS Enterprise, among others. Following the outbreak of the COVID-19, the Esri has partnered with several private organizations around the world to launch the “Esri COVID-19 Resources and GIS Hub”, featuring a compilation of datasets, dashboards, applications, and other helpful resources to facilitate adequate planning against the pandemic. Additionally, Esri has joined forces with various government agencies around the world to help them exploit GIS technology for taking proactive measures to manage the COVID-19 spread [160].

C. BLUETOOTH

Bluetooth is one of the most useful technologies used for accurate proximity calculation. It is also one of the least invasive technologies since it does not monitor the exact location of a cell user but rather the relative distance between his device and that of another. Bluetooth contact tracing applications generally monitor the proximity between two people by calculating the distance between their devices using the Received Signal Strength Indicator (RSSI) measure. Such apps store records of all of a device’s prior Bluetooth connections, including the time for which it maintained a Bluetooth connection with another device. In case a person is diagnosed with the COVID-19, these apps can leverage the Bluetooth connection history of that device to trace all the people who had exposure to the infected individual. These apps can make it simpler for the authorities to effectively determine potential COVID-19 patients and use appropriate measures to quarantine them. Some of the apps that use the Bluetooth technology for contact tracing are mentioned below:

1) TraceTogether

TraceTogether is a contact tracing app launched by the Government of Singapore, which uses Bluetooth technology to determine the history of exposure of an unaffected individual to an infected one. Whenever two people with this mobile application come into close contact with each other, an encrypted code is transferred between their devices and

stored in their apps, provided that Bluetooth is turned on in both the devices. If a person with this app is later diagnosed with the COVID-19, the authorities can check the records stored in his/her app to trace all the people who had come into close contact with the infected person. This app does not use GPS to pinpoint a user’s location, thereby allaying the fears of those people who are worried about their privacy. As on 1 April 2020, nearly 1 million downloads were recorded for this app, which incidentally is a record for the highest number of downloads for an application hosted by a government website in Singapore [161]. However, this number is still not considered to be enough by the Government of Singapore as the reliable functioning of this application requires participation from everyone in the country, and 1 million corresponds to just one-sixth of Singapore’s entire population.

2) APPLE & GOOGLE’S JOINT CONTACT TRACING TECHNOLOGY

In light of the current health crisis, two Silicon Valley tech giants, Apple and Google, have teamed up for a rare joint venture to help governments and medical organizations around the world in their fight against the COVID-19. They plan to develop a privacy-preserving framework that incorporates “application programming interfaces (APIs) and operating system-level technology” to assist public contact tracing applications [162]. In a bid to safeguard user’s privacy, the framework is set to use only the Bluetooth technology for tracking the spread of the COVID-19. Furthermore, the two companies claim that data from the user’s smartphone will not be made available to anyone without the user’s consent. Their framework will enable contact tracing applications to use Bluetooth Low Energy (BLE) technology to log people’s interactions and keep track of whether a smartphone owner has come into contact with someone who is later diagnosed to be COVID-19 positive. If indeed, this scenario takes place, the user is sent an alert stating that he/she has come into contact with someone who is now diagnosed with the disease. Once alerted, such users can then self-isolate or get themselves tested. At present, the framework is still in the development stages, with the API expected to be launched in May, while the OS-level technology to be rolled out in the following months. The draft technical documentation for the framework can be found in [163], and the overview of the API’s working can be found in [164].

D. GPS

Global Positioning System (GPS) is a satellite navigation system owned and maintained by the United States government that provides users with positioning, navigation, and timing (PNT) services [170]. By leveraging this technology, government authorities around the world can monitor the real-time location as well as the historical location of COVID-19 positive patients in their country, which can subsequently enable them to trace other potential COVID-19 patients. Mentioned below are official contact-tracing apps of two countries that make use of the GPS technology:

TABLE 8. Challenges associated with the implementation of various technologies in mobile applications.

Technology	Challenges/Limitations	Plausible Solutions
Bluetooth	Bluetooth signals can sometimes pass through walls, so people in different rooms could be unnecessarily flagged as having had contact [165].	Compute intersection of the users' trajectories in order to have a more robust contact tracing app.
	The range of Bluetooth is significantly higher than the distance recommended for social distancing. Therefore, the use of Bluetooth-based contact tracing apps can often lead to a deluge of false positives.	At present, there is no way to overcome this limitation.
	Low-level functionality of Bluetooth may sometimes be implemented differently across different Bluetooth chip-sets [166].	Need for a standard Bluetooth hardware stack.
	Most contact tracing mobile apps using Bluetooth maintain a centralized database to record all interactions between individuals, which raises several privacy concerns [167].	Need for a decentralized record to prevent authorities from misusing any user's data.
GPS	Extremely low precision of GPS renders it inadequate to be used as the sole technology in contact tracing applications.	Since nothing can be done about either of its shortcomings, developers should focus on adopting other technologies as the underlying architecture for contact tracing applications.
	GPS location can allow authorities to track users' absolute location, which poses a significant risk to users' privacy [165].	
Geo-Fencing	Telecom Companies end up with a lot of data that could infringe the privacy of citizens.	Proper legislation on fair use of the data gathered during such emergencies, and appropriate encryption & deletion of such data as a matter of law.
	No standard protocol for information sharing between different operators.	Need for efficient data sharing formats and uniformity in protocols since the networks are maintained by private contractors.
	When the WiFi location is not available, the accuracy of geofencing contact tracing apps degrades considerably [168].	Creation of geofences using a larger radius [168].
Blockchain	Lack of technological awareness about blockchain among the general public.	Use of social media and other public platforms to make people aware of the fundamental concepts regarding the distributed ledger technologies (DLTs) and their features.
	Scalability issues and concomitant performance issues.	Distributed Acyclic Graph (DAG) data structure is being touted as the solution to the blockchain's inherent scalability issues. Currently, however, almost all DAG-enabled platforms exist just in theory.
Voice Detection	Results yielded by the voice detection apps may be misconstrued by the general public to be as reliable as laboratory tests [169].	Proper disclaimers to ensure that people do not misinterpret the results.

1) AAROGYA SETU APP

The National Informatics Centre, a subdivision of India's Ministry of Electronics and IT (MeitY), has recently developed a contact tracing app called Aarogya Setu to help curb the spread of the COVID-19 in India. Any Indian citizen can download this application for free and register using their mobile number to use this app's services. On launching this application, it asks the user if they are facing any symptoms of the COVID-19, or, if they have an international travel history; if not, the user is classified as belonging to the green zone. This application currently supports 11 Indian languages and is available for both iOS and Android users [171]. Unlike TraceTogether, this app uses the GPS location of the cellphone user in addition to the Bluetooth technology to determine if an individual has been exposed to any potential COVID-19 patient listed in its database [172]. In a scenario that an individual belonging to the green zone comes in contact with someone who is later marked as belonging to the

red zone, this app immediately sends an alert to the former, notifying him/her of the guidelines that he/she should follow. Additionally, this app provides its users with easy access to relevant information [172]. On its release, the Aarogya Setu app became instantly popular among the Indian public. The app garnered over 10 million downloads in just five days of its launch. In response to the privacy concerns surrounding the app's use of GPS technology [173], the Government of India (GoI) has assured its citizens that the data which the app collects is encrypted and will not be used for any purpose besides contact tracing.

2) HAMAGEN APP

A contact-tracing app called HaMagen launched recently by Israel's Health Ministry, has sparked massive interest from the governments of Italy, Australia, and Germany, among others. HaMagen makes use of the GPS technology to determine if any app user has come in contact with someone

who has been tested positive for the disease. Quashing the rumors surrounding the application's privacy pitfalls, the Health Ministry has issued a statement maintaining that any user's private data does not leave the phone without his/her consent. The app's functioning relies heavily on the user's self-reported information regarding their exposure to the COVID-19. Within the first week of the app launch, around 50,000 app users claimed that they had adopted the measure of self-isolation [174].

E. VOICE DETECTION

Following the COVID-19 outbreak, several voice-detection apps have been developed for COVID-19 screening. Voice detection applications require users to voluntarily provide a sample of their voice, based on which the app decides whether or not a person has symptoms of the COVID-19. Two prominent attempts at developing such voice detection platforms for COVID-19 screening have been discussed below:

- An automated AI system has been designed by a team of researchers from Carnegie Mellon University to detect the presence of the COVID-19 in an individual based on his/her voice. After logging in to the app, a user is asked for his height and weight, followed by a request to cough three times. Post this, he/she is asked to recite an alphabet and a vowel loudly, which finally helps the app in measuring the lung capacity of the user by comparing it with thousand's of other users' data, including those who are infected [169]. By the end of this brief process, the user is given a score out of 10. A higher score indicates that a user's features are highly similar to the features exhibited by COVID-19 patients. The researchers, however, have added a word of caution stating that this is not a diagnostic process and can never be substituted for tests conducted in the hospitals and the laboratories [175].
- A similar mobile application for voice-based COVID-19 diagnosis has also been developed by students of the DY Patil Institute of Bio-Technology and Bio Informatics, Mumbai, India [176]. This app is currently being tested at the University of Tor Vergata in Rome, Italy. To use the app, one has to speak into the microphone of his/her device, following which the app breaks the sound into multiple parameters, including frequency and noise distortion. The values of these parameters are then compared to an average person's parameter values to determine if an individual is potentially infected with the COVID-19 [177].

F. CHALLENGES

Although many people have hailed the efforts made by various governments and organizations in building contact tracing apps [178], a school of thought exists that believes that contact tracing applications, even the ones that claim to respect user's privacy, are not secure and can blatantly abuse the privacy of people [179]–[182]. In addition to the

privacy concerns associated with the use of contact tracing apps, several issues in terms of accuracy and reliability also impede their performance (refer to Table 8).

It has become quite evident that the COVID-19 is here to stay unless adequate measures are taken to fight it effectively. Governments and health officials alone cannot vanquish the current health crisis. People around the world need to work collectively with their governments to expedite the end of this pandemic and get things back to normalcy. For example, most of the tools mentioned above require the support of the masses to yield fruitful results. The mere presence of technologies such as smart thermometers and smart wearables is meaningless unless people are willing to use them to fight COVID-19. The use of telemedicine platforms is inconsequential unless patients are willing to trust their health experts. Even the most straightforward contact-tracing apps are worthless unless people are willing to use them when they venture out of their homes. In the coming times, the actions taken not just by the governments, but also by the people, would influence the extent of the havoc wreaked by the COVID-19 pandemic.

XV. ARTIFICIAL INTELLIGENCE

Since its inception, AI has proved to be a landmark technological advancement. If used properly, it stands to be a highly effective tool against the COVID-19 pandemic [183]. Mentioned below are some of the actual and potential ways in which AI can aid the authorities in effectively combating the COVID-19 pandemic:

- Disease Surveillance
- Risk Prediction
- Medical Diagnosis and Screening
- Curative Research
- Virus Modeling and Analysis
- Host Identification
- Busting Fake News
- Enforcing the Lockdown Measures

In the subsections that follow, we review all of the aforementioned applications in detail.

A. DISEASE SURVEILLANCE

The timely surveillance and forecast of diseases, especially the ones with the ability to lead the world into a state of disarray, is crucial. To this end, a Toronto-based health surveillance company, BlueDot, was successful in reporting an impending outbreak of coronavirus on 31 December 2019, nine days before the WHO [184]. BlueDot's AI model leverages several machine learning (ML) and natural language processing (NLP) tools to look for evidence of emerging diseases. This model has allowed BlueDot to track the spread of the SARS-CoV-2 and forecast its outbreak well before epidemiologists. However, that does not go as far as saying that no human effort was required to do the same. While their AI model was able to give predictions in regards to the

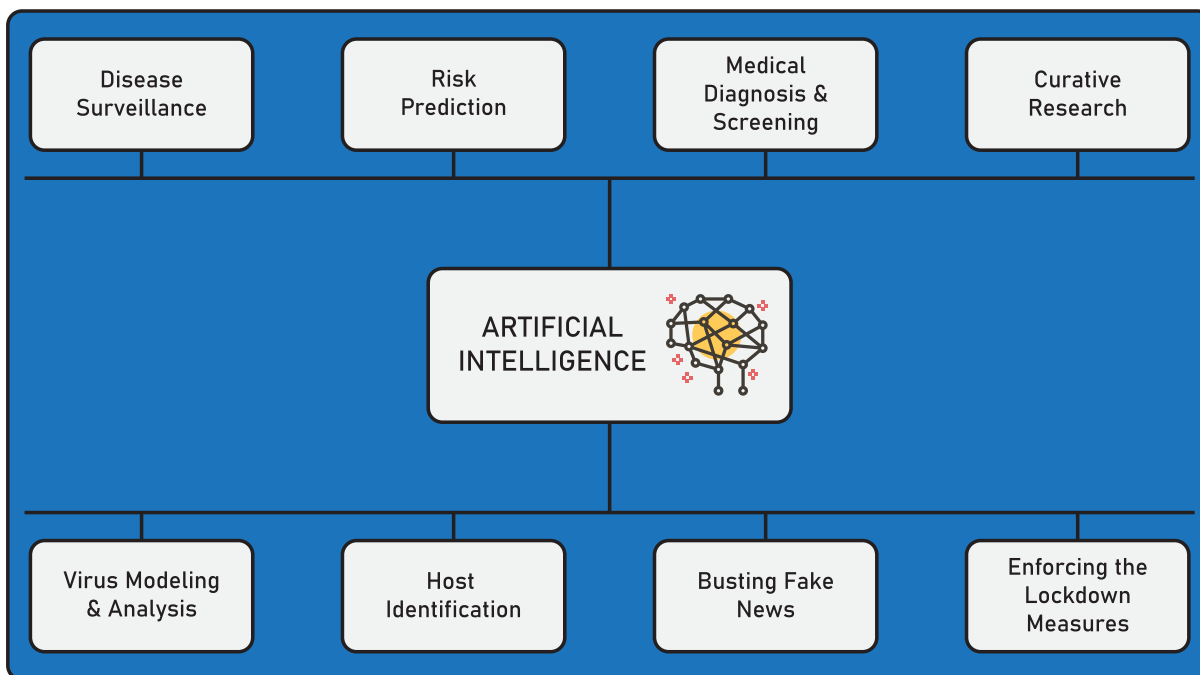


FIGURE 11. Applications of AI for COVID-19 pandemic impact mangement.

outbreak of the disease, human interpretation of the model's output remained central to its working [185].

Besides BlueDot, several other organizations have adopted the use of AI to estimate the risks associated with emerging infections. For example, a risk analytics company founded in 2008, Metabiota, has developed an epidemic monitoring platform that allows it to forecast the spread of diseases. Metabiota bases its predictions on factors like the infection's clinical features, fatality rate, and the availability of treatment. Other functionalities of Metabiota's Epidemic Tracker include providing detailed information and up-to-date statistics on over 120 novel pathogens [186].

In addition to these efforts, a few scientists have also proposed the use of such technologies in identifying potentially fatal zoonotic viruses well before they cause damage to the human population. The Global Virome Project (GVP) is an example of one such endeavor. The GVP aims to establish a genetic and ecological database of viruses in various animal species that are capable of infecting humans. The large volume of data that they collect on viruses could also be used to shape AI technologies to predict which zoonotic viruses have the potential to cause the most harm to the human species. Such mechanisms can allow for the proactive development of vaccines, drugs, and preventive measures [187].

B. RISK PREDICTION

One of the possible avenues of application of AI against COVID-19 is risk prediction (refer to Fig. 11). Broadly, risk prediction can be classified into the following categories [188]:

- Predicting the risk of getting infected.
- Predicting the risk of developing severe symptoms once infected.
- Predicting the risk of using a specific line of treatment on an infected person.

Typically, the risk of getting infected is a function of a myriad of factors. These include age, travel history, hygiene habits, current health status, pre-existing health conditions, and family medical history. Direct mathematical modeling of such factors would not yield fruitful results. However, a comprehensive analysis of these factors integrated with AI techniques, can offer a more precise and reliable prevision of individual risk profiles. For example, authors in [189] describe an ML-based stratagem to build a vulnerability index for individuals susceptible to the novel coronavirus.

Once a person is infected, AI capabilities can also be used to determine the probability of survival and the requirement of ICU treatment for COVID-19 patients. To this end, physicians at universities like Stanford and the University of Chicago are making attempts at augmenting their existing AI systems to accurately identify the COVID-19 patients whose condition might worsen. Earlier, these systems have proved their mettle in predicting whether or not heart disease patients will require a transfer to the ICU. In another effort, Bayesian Health, a start-up tracing its roots to the John Hopkins University, has started working on an early warning system for acute respiratory distress syndrome (ARDS), one of the severe symptoms associated with the COVID-19 [190]. The authors of [191] have also proposed an AI framework that leverages predictive analysis performed on real COVID-19 patients to support clinical decision-making. Their AI-powered

predictive model is capable of identifying people with a higher likelihood of developing severe symptoms like ARDS based on initial presentation. According to their results, their model achieved an accuracy of 70-80 % in predicting severe cases of the COVID-19.

In addition to the use-cases mentioned above, AI techniques, particularly machine learning algorithms, can also be used to correlate the patient's data parameters with a specific drug's usage. Such correlations can be used to predict the effect of the drug on a specific group of patients. Pre-emptive knowledge of these factors can enable the doctors and medical suppliers to be better prepared for the consequences.

C. MEDICAL DIAGNOSIS AND SCREENING

Rapid diagnosis of the COVID-19 can allow governments to take effective response measures to limit the disease's further spread. The shortage of testing kits worldwide, however, has made it hard for the authorities to carry out large-scale diagnostic testing. Many existing AI tools are being repurposed, while some new ones are also being built to solve this problem. In this subsection, we examine the various ways in which AI is revolutionizing the process of COVID-19 screening and diagnosis.

1) FACE SCANNERS

Following the COVID-19 outbreak, various authorities used IR temperature scanners at different public places to screen people for a fever. This technology, however, requires the presence of frontline personnel to carry out the scan. To limit the exposure of the frontline staff to potential COVID-19 patients, several hospitals, airports, and medical centers have adopted the use of cameras with AI-based multisensory technology [192]. These cameras can not only enable the authorities to observe the crowds and identify individuals with high body temperatures, but they can also be used to recognize their faces and trace their movements. One of the first hospitals to use this technology was the Tampa General Hospital in Florida, USA. The hospital installed an AI-enabled camera at its entrance to screen all the entering patients for elevated body temperatures by giving them a thermal face scan. Their AI system uses machine learning, and findings of the camera, to classify whether or not an individual is manifesting the symptoms of the COVID-19 [188].

2) MEDICAL IMAGING

AI technology has considerable potential to improve image-based medical diagnosis. According to the researchers at the UN Global Pulse, analysis of computed tomography (CT) scans and X-rays using AI-enabled tools can save radiologists' time by offering more timely medical diagnosis than current tests for the COVID-19 [185]. To this end, multiple efforts have already been made to employ the use of AI-enabled medical imaging to diagnose the COVID-19.

- A Beijing-based start-up that specializes in building an oncology data platform and performing medical data

analysis, LinkingMed, has put forth an AI-based model for screening pneumonia through CT scan analysis. Since pneumonia is one of the most common clinical features of the COVID-19, identifying the presence of pneumonia can help identify potential COVID-19 patients. LinkingMed's open-source AI model is based on Baidu's parallel distributed deep learning platform - PaddlePaddle [192].

- A joint effort between the researchers at the University of Waterloo and an Ontario-based AI start-up, DarwinAI, has yielded a Convolutional Neural Network (CNN) to diagnose COVID-19 using chest X-rays. Labeled COVID-Net, this AI algorithm has been made open source by the research team to facilitate the development of AI tools over their model.
- Another AI model for diagnosing the COVID-19 using X-rays has been put forth by a few researchers at the Delft University of Technology, Netherlands. Named CAD4VOCID, this model is built on top of an AI model developed at the same University for the diagnosis of tuberculosis.

Although the use of AI-powered medical imaging techniques has been perceived to have great potential in COVID-19 diagnosis, several radiologists have voiced some issues concerning such techniques. Firstly, the lack of unbiased data hinders the performance of AI models. Secondly, the use of medical imaging techniques can potentially contaminate the equipment used, and may well cause the disease to spread further [185].

3) AI-POWERED MEDICAL DIAGNOSIS IN SOUTH KOREA

In the Republic of Korea, several AI-powered tools have helped the country in quick examination and identification of COVID-19 patients. An algorithm to detect unusual observations in the patient's chest X-rays, VUNO's Chest X-Ray Image Support Decision Tool, has the potential to recognize the individuals in need of intensive care. To do so, the algorithm studies the patient's X-ray images and examines whether or not there is an issue with the patient's lungs. Another AI-platform named AiHub has been developed in the Republic of Korea by an AI-based medical and security solutions company - JLK inspection. The platform uses the AI and big data capabilities of several imaging devices to diagnose any lung conditions that the patient might have, in a matter of seconds. In addition to various COVID-19 diagnosis platforms, AI has also played an essential role in accelerating the development of testing kits in Korea. These testing kits have been approved by not only the authorities in Korea but also by the European Union [193].

4) COVID-19 VOICE DETECTION SYSTEMS

Voice detection is one of the simplest technologies that can be employed to identify potential COVID-19 patients. During these difficult times, when there is a serious dearth of testing kits, voice detection platforms can act as a screening measure

to decide who needs to be tested. For more details on how voice detection platforms are currently in use, kindly refer to section XIV-E.

From all the examples presented above, it is crucial to note that AI is better suited to assist the screening of COVID-19 patients rather than diagnosing them altogether. To be able to diagnose any COVID-19 patient accurately, AI devices, platforms, and algorithms must be sufficiently robust so as to detect all possible mutations of the virus.

D. CURATIVE RESEARCH

Being novel, one of the major problems with the SARS-CoV-2 is the lack of existing research and treatment protocols for the virus. However, by analyzing the current cases of the COVID-19 as well as the existing research on different diseases, AI can prove to be a beneficial technology to speed up the process of drug development. Several organizations and research labs have already adopted the use of AI to identify potential treatments for the COVID-19. AI can not only expedite the drug development process, but it can also aid in the process of discovering existing drugs.

1) DRUG DEVELOPMENT

Machine learning (ML), a subset of AI, has proved its effectiveness in the process of drug development in the times of previous health emergencies. For example, during the Ebola epidemic, Bayesian ML models were used to speed up the process of discovering molecular inhibitors against the virus [194]. Similarly, the authors of [195] adopted the use of ML-assisted virtual screening and scoring to speed up the process of discovering viral inhibitors against the avian H7N9 virus responsible for recurring influenza epidemics in China. In light of the current pandemic, ML models similar to such models can aid in expediting the process of developing drugs that can possibly be used to treat the COVID-19.

2) REPURPOSING EXISTING DRUGS/COMPOUNDS

In addition to being able to aid in drug development, scientists are also using AI to help in identifying existing drugs that can be repurposed to treat the COVID-19.

- A Germany-based start-up named Innoplexus AG has exercised the use of its AI-powered drug discovery platform to identify a combination of existing drugs that may prove useful in the treatment of the COVID-19. After extensive analysis of existing data associated with the COVID-19, their platform has revealed that Chloroquine, an anti-malaria drug, may work better in combination with Remdesivir (an experimental antiviral originally developed to treat Ebola) or Tocilizumab (an immunosuppressive drug) or Pegasys (used to treat Hepatitis B & C) or Clarithromycin (an antibiotic) [196].
- A similar effort is being made by a British start-up named Exscientia in collaboration with Diamond Light Source, UK and Calibr, a division of the California-based Scripps Research Institute. Exscientia

aims to use its AI drug delivery platform to arrive at a combination of compounds that could prove to be beneficial in treating the COVID-19. To do so, Exscientia intends to screen some 15000 clinically-ready molecules present in Calibr's compound library against three key viral drug targets of the SARS-CoV-2 [197]. Earlier this year, Exscientia developed the first-ever AI-created drug to enter the clinical trials [185].

- Researchers from the Republic of Korea and the USA are using deep learning to investigate the effectiveness of an existing antiretroviral drug used to treat HIV/AIDS named Atazanavir, in the treatment of the COVID-19 [198].
- Researchers at a UK-based AI company, Benevolent AI, have identified Baricitinib (a drug for the treatment of rheumatoid arthritis) as a potential drug to treat the COVID-19. Following their research, Baricitinib has entered a controlled trial with the United States National Institute of Allergy and Infectious Diseases (NIAID) [198].
- Gero, AI-powered drug discovery and drug repurposing platform developed by a group of scientists in Singapore, has assisted in the identification of several existing drugs, including a drug named Afatinib (used to treat non-small cell lung cancer), that could potentially be used to treat the COVID-19 [185].
- Various ML techniques are also being used to identify drug candidates by predicting drug-target interactions (DTIs) between the virus's proteins and existing drugs. The authors of [199], for example, built a deep learning Deeper-Feature Convolutional Neural Network (DFCNN) system that can identify/classify protein-ligand interactions with reasonably high accuracy. Thus, the use of AI can not only help in suggesting possible candidates for treatments but also analyze their expected effectiveness. Another example of this approach is given in [200], where a deep learning-based drug-target interaction model Molecule Transformer-Drug Target Interaction (MT-DTI) has been developed to identify commercially available drugs capable of acting on SARS-CoV-2 viral proteins.

Although much effort is being put into the discovery of such treatments, it is highly unlikely that any of them will be available shortly. These candidate treatments have to undergo extensive scientific checks and clinical trials before they are approved for commercial use.

E. VIRUS MODELING AND ANALYSIS

The key to developing a successful treatment against COVID-19 is to understand the virus itself. Since viruses cannot reproduce by themselves, they rely on host cells to manufacture copies of their DNA. To do this, a virus typically infects a host cell by binding itself to the host's receptors via a lock and key mechanism. The working mechanism for most inhibitor-based agents is to prevent this from happening by

MYTHS	COVID-19	FACTS
❄️ The COVID-19 can be transmitted over 5G networks.		❄️ The COVID-19 cannot travel over radio waves.
❄️ Hand dryers can be used to kill the SARS-CoV-2.		❄️ Hand dryers are not effective in killing the SARS-CoV-2.
❄️ The SARS-CoV-2 can be spread via mosquito bites.		❄️ To date, there is no evidence to support this statement.
❄️ Cold weather and snow can kill the SARS-CoV-2.		❄️ Cold weather and snow cannot kill the SARS-CoV-2.
❄️ Drinking alcohol can protect you against the COVID-19.		❄️ Alcohol consumption may add to your health problems.
❄️ Eating garlic can help prevent the COVID-19.		❄️ Garlic, although healthy, cannot prevent the COVID-19.
❄️ The COVID-19 can only affect the older people.		❄️ The COVID-19 can affect people of all age groups.
❄️ Taking a hot bath can help prevent the COVID-19.		❄️ Taking a hot bath does not prevent the COVID-19.
❄️ Catching the COVID-19 disease means you have it for life.		❄️ You can recover from the COVID-19.
❄️ Thermal scanners can detect the COVID-19 infection.		❄️ They can only detect the presence of a fever.

FIGURE 12. Debunking myths surrounding the COVID-19 (information source: WHO).

blocking the receptors of the target cells. Thus, the design of effective inhibitors requires scientists to model the binding mechanism. Machine learning happens to be one of the most useful tools in the scientist's arsenal for building such models.

In the past, ML models trained with protein data have proved to be successful in predicting protein-protein interactions (PPIs) between the H1N1 virus and human body cells, thereby eliminating the need to model the entire virus-host interactome [188]. Machine learning can also be used to model various protein folding mechanisms that the virus uses to sustain itself. Reference [201], for example, employs deep learning algorithms to predict the structure of a protein from its amino acid sequence. Knowing a protein's three-dimensional structure is of great importance, as its functioning is strongly correlated to its structure.

Amid the current COVID-19 health crisis, DeepMind, Google's AI company, has adopted the use of its AlphaFold system to predict the structure of the proteins associated with the SARS-CoV-2. These predictions can aid scientists in better understanding the overall structure of the virus, and consequently, in developing a new drug to treat the COVID-19 [185]. It is important to note, however, that DeepMind has made it clear that these predictions have not been experimentally verified [188].

F. HOST IDENTIFICATION

The SARS-CoV-2 is a member of the BetaCov genera of the coronaviridae family. Typically, genomes of such viruses are a mix of bat and rodent genomes. To date, the mammalian host that facilitated the transmission of the COVID-19 to

human beings is an unknown variable. To this end, ML models can be used to effectively compare the viral genome with known genomes and identify similarities between them. Such a database of known genomes is available in [202]. In [203], the authors have proposed the use of a random forest algorithm to identify the hosts for the influenza-A virus. Another example of such an approach is given in [204]. Such models can be extended to include the SARS-CoV-2 as well.

G. BUSTING FAKE NEWS

The uncertain times following the outbreak of the COVID-19 have bred several myths and conspiracy theories (refer to Fig. 12). Much misinformation has been making the rounds on social media platforms. To curb the propagation of these fake news and provide verified information, technology companies like Google, Youtube, and Facebook have employed the use of AI techniques. All these platforms have made an effort to screen content for the presence of even the slightest bit of misinformation. Youtube, in particular, has placed stringent measures to take down any video propagating fake news [192].

H. ENFORCING THE LOCKDOWN MEASURES

Many countries around the world, including China, India, the USA, and the UK, are adopting the use of AI to enforce social distancing and lockdown measures. In China, Baidu, one of the largest AI and internet companies in the world, has developed computer vision (CV) powered infrared cameras to scan public places. These cameras can not only identify

people with high body temperatures, but via the use of their inbuilt facial recognition system, they can also recognize citizens who are not following the lockdown measures. A similar CV camera system has been deployed in Oxford, England, to monitor if the crowds are following the social distancing measures. An AI-based start-up in the USA - Landing AI, helmed by one of the most renowned AI experts in the world - Andrew Ng, has also developed a social distancing detection tool that monitors crowds and alerts the authorities whenever social distancing guidelines are breached [185].

I. CHALLENGES

Artificial Intelligence can conceivably play an essential role in mitigating the impact of the COVID-19 pandemic. However, at present, AI systems are still in the prefatory stages. The several challenges and limitations hindering the application of AI in COVID-19 impact management are as follows:

- i) To yield reliable and accurate results, AI models require a substantial amount of training data. However, owing to the unprecedented nature of the pandemic, there is a dearth of historical data on which to train AI models, which has consequently rendered several AI models inefficient [185].
- ii) It is not only the absence of open data that has impeded the performance of AI models, too much noisy and outlier data has also presented a challenge to the efficient use of AI technologies. Google Flu Trends' failed initiative sheds light on the fact that a deluge of data hubris can potentially inundate AI algorithms and inhibit their functioning [185].
- iii) Another limitation faced by AI systems, particularly machine learning models, is their inherent assumption that all possible contingencies in any given situation are the same as the ones exhibited in the dataset they have been trained on [185].
- iv) The use of AI techniques for crowd surveillance is seen by many as a breach of privacy. Although at present, people have apprehended the fact that public health concerns are more important than data privacy concerns, the privacy pitfalls associated with the use of AI have instilled a sense of fear among the public that governments may continue to monitor them even after the pandemic is over [184].
- v) Another limitation of AI in its current form is its dependence on human knowledge. Human expertise is fundamental to guide the implementation of AI techniques and make a significant difference in the fight against the COVID-19 pandemic [184].

Despite the several challenges facing the AI systems, their contribution to the fight against the COVID-19 pandemic cannot be overlooked. In recent years, AI technology has made stunning advances in the fields of NLP, ML, deep learning, data analytics, among others. Such developments serve to prove the potential of AI in assisting the COVID-19 pandemic management system.

XVI. BLOCKCHAIN

Blockchain technology has been under extensive deliberation amongst researchers and industrialists in recent times, especially since the onset of Blockchain 2.0 & Blockchain 3.0 [205]. Gradually, this technology is extending its presence to almost all the major domains, including the insurance sector, the transportation industry, drone communication technologies, and even the healthcare sector [206], [207]. The current health crisis, brought by the COVID-19, is neither localized nor independent. The COVID-19 pandemic has left no space for seclusion, and people all around the globe need to stand united to get through this crisis. The nature of the pandemic itself is distributed in nature. Therefore, distributed ledger technologies, such as blockchain, can be highly beneficial in regards to dealing with this situation. Blockchain technology enables individuals and organizations from any corner of the world to become a part of a single interconnected network that facilitates the secure sharing of data. The tamper-proof feature of blockchain makes it resistant to unauthorized changes, and the use of consensus algorithms and smart contracts minimizes the potential of the dissemination of bogus data and fraudulent information. Blockchain-based applications can be employed to monitor and manage the COVID-19 patients digitally, thereby relieving some burden on the hospital staff and other healthcare personnel (refer to Fig. 13). Mentioned below are some of the significant ways in which blockchain technology can help in the fight against the COVID-19:

- Facilitating Increased Testing and Reporting
- Recording the Details of the COVID-19 Patients
- Managing the Lockdown Implementation
- Preventing the Circulation of Fake News
- Enabling an Incentive-Based Volunteer Participation Platform
- Enabling a Secure Donation Platform for Supporters
- Limiting Supply Chain Disruptions

We dissect each one of these ways in the subsections that follow.

A. INCREASED TESTING AND REPORTING

Various countries, such as China, Germany, and the Republic of Korea, have emphasized the need for extensive testing of individuals as the eventual means to curb the spread of the virus. However, in order to ensure efficiency, tests must be carried out intelligently, and accurate data in regards to the number of tests performed needs to be maintained. To this end, blockchain technology can help in setting up distributed check-up points for testing the patients who are showing symptoms related to COVID-19. The coordinators of all these check-up points can act as nodes of the same distributed blockchain network. These nodes can continuously update data regarding the number of tests performed and the number of laboratory-confirmed cases in their local check-up point on this network. This can help in getting an accurate report on the number of tests being conducting and the number of

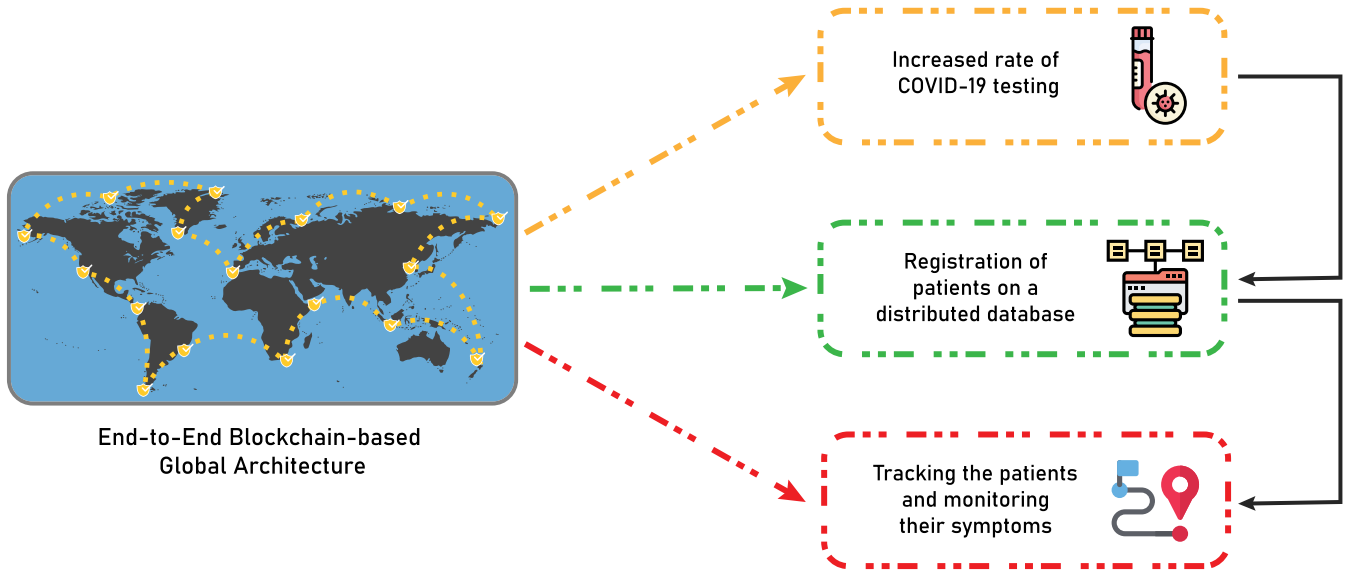


FIGURE 13. Blockchain-based DLT architecture for COVID-19 impact management.

positive cases recorded in each area. These reports can further help the authorities and healthcare officials to strategize a plan to combat the spread of disease in the areas reporting a high number of COVID-19 positive patients. The shared blockchain network can act as a single source for all the users to update and retrieve the data. Due to blockchain's inherent feature of being immutable, data stored in the network will be tamper-proof and can, therefore, be trusted by all the healthcare professionals and government authorities.

B. RECORDING COVID-19 PATIENT DETAILS

Apart from securely storing the test reports, the blockchain-based distributed platforms can also act as a promising solution for recording COVID-19 patient details. As soon as a person tests positive for the COVID-19, all of his/her details, including sex, age, medical history, underlying health conditions, the severity of the disease, the symptoms developed, and the recommended line of treatment, can be securely added on the network. A platform with up-to-date data on the COVID-19 patients can help facilitate the study of the disease's clinical characteristics and help all the health centers that are part of the network, better understand better the disease's growth pattern. In the near future, any health center dealing with a confirmed case of the COVID-19 can refer to these studies to anticipate the kind of facilities and medicines required to deal with the situation at hand.

C. MANAGING THE LOCKDOWN IMPLEMENTATION

Living under lockdown conditions is an unprecedented situation for a majority of the people around the world. The essential needs of the public have to be met to empower them to stay at home and follow the lockdown restrictions strictly. People from the police department, healthcare department,

Non-Governmental Organizations (NGOs), and other volunteers need to work in sync with the government authorities to achieve the intended results of the lockdown successfully. Following the implementation of lockdown measures, multiple reports have surfaced claiming that people residing in easily accessible areas are utilizing extra services while people living in remote areas are kept bereft of even the fundamental necessities. To this end, blockchain technology can aid the government and non-government bodies to oversee the requirements of people in different regions of the country and efficiently manage the lockdown implementation. All the authorized groups or individuals associated with enforcing the lockdown can act as nodes in the blockchain network and can register the needs of the residents in their designated area on the network. All the participating nodes in the blockchain network are allowed to check for the requirements listed by the nodes of different areas, following which the intended groups may take appropriate actions to satisfy those needs. This will help to limit the imbalance in the supply of services in different areas and consequently result in a more stringent lockdown implementation.

D. PREVENTING THE CIRCULATION OF FAKE NEWS

Following the outbreak of the COVID-19, one of the major concerns for governments worldwide has been to limit the spread of misinformation. Various unsolicited messages are being forwarded, giving rise to feelings of unrest amongst the citizens. Besides spreading rumors and fake news, some messages are particularly inflammatory and instill the feelings of xenophobia amongst the readers. However, since several social platforms are currently in use, it becomes difficult for the authorities to monitor the authenticity of the information being shared in each of these platforms. Moreover, even if the

authorities are able to detect an unfactual message, it becomes difficult for them to track the original initiator of the message. To this end, the use of a public blockchain network for information sharing can be a highly promising solution to curb the spread of rumors, conspiracy theories, fake news, and inflammatory remarks. By forcing all message initiators to sign their message with a digital signature, the authorities can keep track of who shared which message. Although the use of consensus algorithms will ensure that no misinformation makes it into the network in the first place, even if it does, the authorities can quickly determine the message initiator based on his/her digital signature. Such a platform will prevent people from falling prey to fraudulent information.

E. INCENTIVE BASED VOLUNTEER PARTICIPATION

The general behavior of the individuals is that they tend to respond quickly to the incentives offered. Incentives may be simple words of appreciation, a monetary benefit, a small gift, or a certificate acknowledging his/her work. Blockchain technology makes use of a robust consensus mechanism that can be used to facilitate the secure distribution of incentives in different ways to the deserving candidates [208], [209]. In the current state of crisis that is scaling up at a rapid pace, it becomes crucial for countries to prompt their citizens to share vital data and also to involve them in impact management activities [210]. To this end, a blockchain-based incentive mechanism, such as the ones proposed in [211], and [212], can prove to be highly useful in motivating a large number of citizens to act as volunteers for the COVID-19 crisis management. Volunteers can help by distributing food, masks, and other essential products. Furthermore, they can also help by reporting the identities of people 1) breaking social distancing protocols, 2) hoarding items of daily use, and 3) misusing the current state of panic among people to charge them extra for even the most fundamental necessities. All the participants in the blockchain network can be rewarded with some tokens or certificates of appreciation to acknowledge their work done and motivate them to participate with even more enthusiasm.

F. SECURE DONATION PLATFORM

Following the massive impact of the COVID-19 pandemic globally, especially on those belonging to the underprivileged class, several people and organizations around the world are coming forward to help the ones less fortunate than themselves. Since, in these dire times, not everyone cannot go out and personally help the needy, people have chosen to donate in several international and national relief funds. However, the reports of fraudulent bank accounts and relief funds have instilled a feeling of insecurity among the people who were otherwise willing to donate. Recently, in India, a group of fraudsters was caught collecting donations by creating a fake bank account under the same name as the one initiated by the Indian prime minister [213]. To this end, a secure and transparent donation platform is required to quash the skepticism surrounding the validity

and transparency of existing donation platforms and, consequently, enable more citizens to extend monetary help. Various blockchain-based crowdfunding platforms have been proposed in recent times [214], [215]. Blockchain-based platforms can ensure a secure collection of money while also warranting transparency in regards to where the donated money is being used.

G. LIMITING SUPPLY CHAIN DISRUPTIONS

The onset of the COVID-19 has been particularly troublesome for international trade and supply chains. Amid the lockdown measures currently imposed in several countries, most organizations around the world are experiencing considerable difficulties in maintaining the flow of goods and services [216]. Supply chain disruptions, further exacerbated by trade restrictions, have caused a majority of suppliers to halt production and several logistic partners to postpone the transport of goods. Technologies, such as blockchain, are being hailed as the key to reforming the trade networks and making the supply chain more tolerant of such emergencies in the future.

The past few years have seen several attempts made by organizations around the world to incorporate blockchain in their supply chains in a bid to increase supply chain visibility, lack of which is cited as the primary reason for supply chain disruptions. In existing systems, even if the manufacturers are familiar with any difficulties being faced by their immediate suppliers, they might be oblivious to the challenges faced by their supplier's partners. Knowledge of such challenges can allow manufacturers to arrange for temporary solutions to deter supply chain problems [217]. However, owing to the insecurities of losing a competitive edge, suppliers may be leery of disseminating their partner's details. To this end, permission blockchains can make it feasible for the supplier to share data without actually disclosing their partner's identity.

H. CHALLENGES

A few technical and non-technical challenges hinder the application of blockchain in the COVID-19 impact management. Before blockchain-based solutions can be implemented in the current situation, these issues must be adequately addressed.

- i) The first non-technical challenge to blockchain implementation is the lack of awareness about blockchain and its potential. Furthermore, several people have reservations regarding the use of blockchain since they associate blockchain only with cryptocurrencies and fraudulent activities.
- ii) Although non-technical challenges can be handled by increased awareness, the main challenges to blockchain implementation are the technical ones. Blockchain-based platforms often suffer from their lack of scalability. The current crisis necessitates the use of a highly scalable solution since it is affecting almost all people around the world. Currently, only a few

blockchain-based platforms are available, and almost all of them have inherent scalability constraints.

- iii) The response to the current pandemic requires the consolidation of various emerging and legacy technologies. Since blockchain technology is relatively new and immature, it becomes difficult to integrate blockchain applications with legacy systems
- iv) One of the significant advantages of blockchain, the absence of any central authority, may sometimes backfire. To ensure the proper functioning of blockchain-based applications, it is essential to properly enforce government regulations and standards in the design and development of such applications.

Although blockchain technology is relatively new and its entire potential is yet to be explored, the disastrous impact of the COVID-19 pandemic has warranted the use of blockchain-based transparency solutions for enhanced impact management techniques. In the coming times, due to the several benefits that it offers, blockchain technology has the potential to become an indispensable part of the healthcare industry and the rapid response system.

XVII. 5G NETWORK TECHNOLOGY

5G refers to the fifth generation of wireless communication technology supporting mobile networks globally [218]. In comparison to 4G, 5G is expected to have better performance in terms of higher speed, lower latency, wider range, increased availability, and more reliability. Together with other concomitant technologies like IoT and AI, 5G network technology has the potential to revolutionize the healthcare sector. The commercialization of 5G technology in China has already transformed its response mechanism to the COVID-19 pandemic by providing better assistance to the frontline staff and facilitating improved virus tracking, patient monitoring, data collection, and analysis [219]. Citing China as an example, in this section, we discuss the various ways in which countries can adopt 5G to help improve the efficiency of their efforts in resisting the COVID-19 health crisis.

A. 5G+ TELEMEDICINE

As defined in section X-C, telemedicine refers to the practice of remotely monitoring the patients. Although the use of drones, smart wearables, and mobile applications can augment the functionalities of the telemedicine sector, 5G network technology is a necessity to realize those functionalities. Due to its limited bandwidth and data transfer speed, the existing 4G networks cannot support real-time high-quality video conferencing, which is an essential requirement for seamless consultation teleconferencing [220]. Furthermore, 4G LTE networks often hinder the connection of IoMT devices to cloud platforms, consequently rendering them inefficient. To this end, 5G with its features like ultra-low latency, and high-speed data transmission can enable mobile networks to address these issues. Furthermore, 5G can

enable immersive virtual and augmented reality (VR/AR) applications, which can conceivably lead to an interactive experience in telemedicine, and equip caregivers to provide immediate expertise in regards to possible complications and treatment strategies [221].

China, where the 5G technology was commercially unveiled in early November last year, has already drawn on some of the features that 5G networks bring to telemedicine. Various hospitals and medical centers in China have launched 5G+ telemedicine platforms for COVID-19 patients. For example:

- West China Hospital has launched a COVID-19 5G+ teleconsultation platform with assistance from China Telecom.
- A hospital affiliated to the Kunming Medical University has launched a 5G-based online platform for free COVID-19 diagnosis and treatment [222].
- An emergency facility in Wuhan, Huoshenshan Hospital, has launched a 5G+ remote consultation platform. This consultation platform has enabled a more efficient diagnosis and treatment of the COVID-19 patients in the hospital, by equipping the healthcare professionals in Beijing to work with the medical team of the hospital [223].

B. 5G+ MEDICAL IMAGING

Recent years have seen medical imaging techniques like Picture Archiving and Communication Systems (PACS), become an indispensable part of diagnosis and treatment. In tandem with the next-generation cellular networks and technologies like AI and big data analytics, PACS can offer enhanced data analysis & management, while requiring minimal human effort. In a specialist field hospital in Wuhan, Leishenshan Hospital, 5G-enabled medical imaging platforms allowed for real-time diagnosis of COVID-19 patients, and in doing so, relieved some of the load on the hospital's medical staff [223].

C. 5G+ THERMAL IMAGING

Thermal imaging technology, initially developed for anti-aircraft defense, has now found its way into several domains, including healthcare, where it has proved to be particularly propitious. The establishment of 5G networks has facilitated the development of 5G-enabled thermal imaging systems that can have several applications in defense and healthcare. A 5G+ IR thermal imaging monitoring system can enable the real-time temperature of moving bodies with high accuracy and precision. The data accumulated by the systems can then be transmitted to the central monitoring system with ultra-low latency using 5G networks. For the COVID-19 outbreak, this functionality can mean around-the-clock public temperature monitoring. In China, several 5G+ thermal imaging systems have already been consolidated in robots and UAVs, which have been deployed in public spaces of several cities to reduce the spread of the COVID-19 [223].

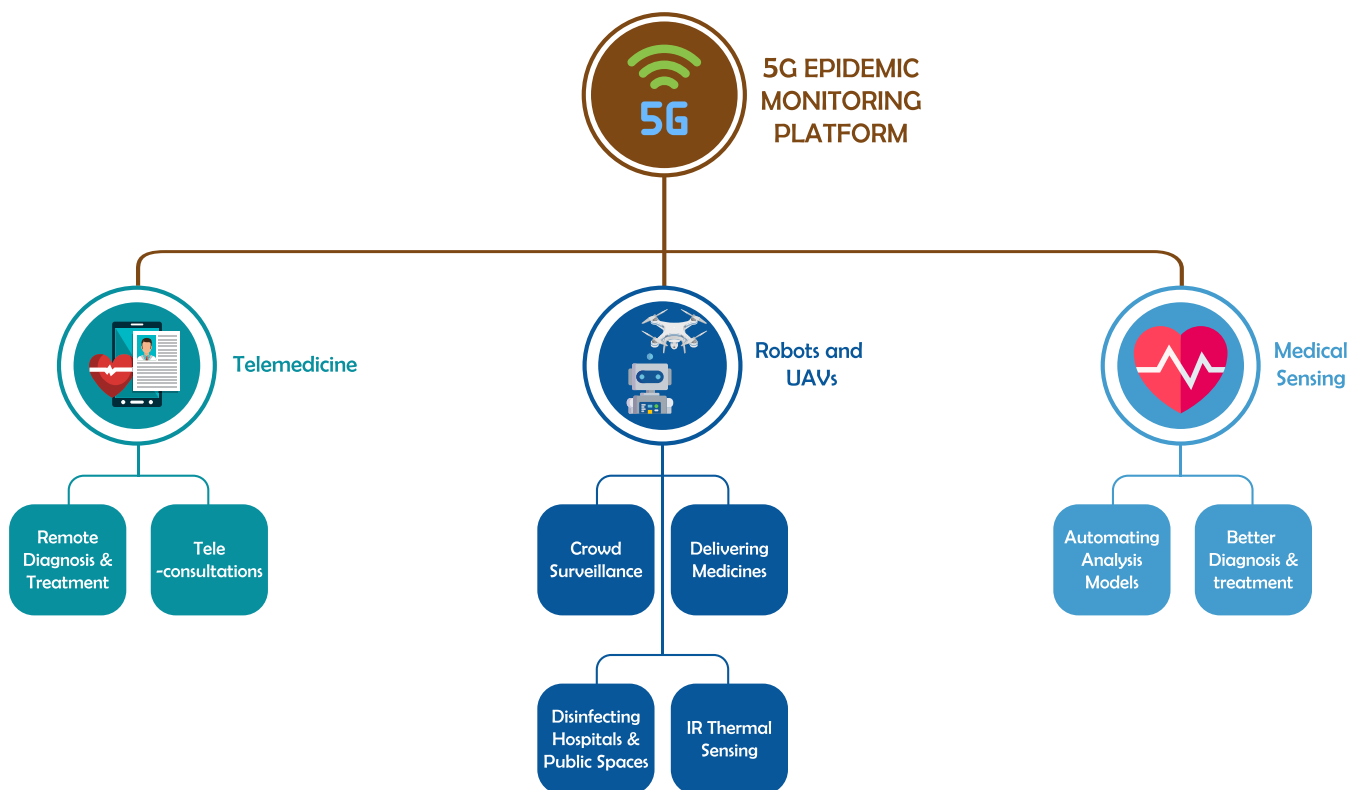


FIGURE 14. 5G epidemic monitoring platform.

D. 5G+ ROBOTS

Following the COVID-19 outbreak, several attempts have been made around the globe to develop and deploy robots to ease the burden on the first-line officials. Although some of these attempts have already been discussed in section XII-A, this section focuses mainly on 5G-powered robots. In addition to having more functionalities, 5G-enabled robots are often more efficient in performing the assigned tasks.

1) 5G ROBOTS DEPLOYED BY AIS IN THAILAND

In Thailand, Advanced Info Services (AIS), the country’s largest phone operator, has leveraged 5G technology in various ways to fight the outbreak of the COVID-19. AIS has installed 5G networks at 20 hospitals and deployed several 5G robots to aid the hospitals in augmenting their telemedicine facilities. Apart from serving as a means of communication between the medics and the patients, these robots have the ability to perform thermal scans [224].

2) CHINA MOBILE’S 5G ROBOTS IN SHANGHAI

As part of its effort to contain the spread of COVID-19, a Chinese telecommunications operator, China Mobile, has provided six 5G-enabled intelligent robots to the Shanghai Public Health Clinical Center. These robots can perform a multitude of operations, such as sanitizing the health center premises and delivering medicines to the patients, to name a few. In addition to the robots, telecom operators in Shanghai have deployed smart devices such as 5G thermal imaging

cameras and 5G health monitors in their bid to combat the COVID-19 crisis [225].

3) CloudMinds’ 5G ROBOTS IN WUHAN

A field hospital, staffed with several 5G-enabled smart robots, was recently opened in Wuhan, China. These robots, provided by a Beijing-based company called CloudMinds, can clean and disinfect the premises, deliver medicine to the patients, and measure their temperature. This facility, commonly referred to as the Smart Field Hospital, also employed the use of various other IoT devices to ease the burden on the hospital staff. Patients at the facility wore smart bracelets and rings that synced with CloudMinds’ AI platform to enable the health workers to continually track their patients’ vital signs, including their temperature, heart rate, and blood oxygen levels, without requiring to be physically present with them at all times [145].

4) PATROL ROBOTS IN MULTIPLE CITIES OF CHINA

A local robotics company based out of Guangzhou, China, has recently designed 5G police patrol robots on top of the Advantech-developed edge computer MIC-770. These smart robots, born at the intersection of AI, IoT, 5G, and cloud computing technologies, are equipped with five infrared thermometers & high-resolution cameras that allow them to measure the body temperatures of up to 10 people at once. Furthermore, by employing the use of environmental sensing, these robots can also determine if someone is wearing a mask

or not. Anytime the robot encounters someone who is not wearing a mask or has high body temperature, it immediately sends an alert to the local authorities [226]. These robots have been deployed in public places of multiple cities in China, including Shanghai, Guangzhou, and Guiyang.

E. CHALLENGES

Since the outbreak of the COVID-19, several technological solutions have been proposed for mitigating its impact. Among them, IoT, drone technology, and AI have been at the forefront. However, to realize the transformative potential of these technologies, there is a need for a cellular network that can overcome the bandwidth, latency, and flexibility issues inherent to the current network technology. The responsibility for this rests with the next-generation 5G cellular networks. The integration of tools like UAVs, robots, and telemedicine platforms with 5G-supported features like high-speed data transmission, ultra-low latency, and advanced data analytics, can allow for an efficient system for monitoring the crowds, detecting infected individuals, and providing treatment to them, all without the need for any physical human contact (refer to Fig. 14). In the future, such an epidemic control system also has the potential to be one of the building blocks for the development of a more dynamic smart city management model [223]. However, at present, the implementation of 5G networks faces several challenges, some of which are mentioned below:

- i) Since the deployment of 5G networks is still in nascent stages, one of its pitfalls is the lack of infrastructure to support their working. Furthermore, the high costs associated with the installation and maintenance of 5G networks have made its wide-scale deployment difficult for governments and telecom operators.
- ii) On their own, 5G networks cannot revolutionize the healthcare sector. They can prove to be effective only when used in tandem with other emerging technologies like IoT, AI, and cloud computing.
- iii) At present, there are no established guidelines that regulate the use of a patient's confidential data collected using 5G healthcare systems. Besides data confidentiality, several other security issues associated with the use of 5G are yet to be resolved [221].

Although the wide-scale deployment of 5G networks in the healthcare industry is likely to take a few years, an increasing number of medical centers are already contemplating the use of 5G-enabled healthcare systems to enhance the quality of medical service and patient experience, reduce the cost of medical care, and minimize the burden on healthcare personnel [221].

VIII. CONCLUSION

While the world continues to grapple with the impact of the COVID-19 pandemic, complementary efforts of various emerging technologies, such as IoT, UAVs, AI, blockchain, and 5G, are endeavoring to alleviate its impact. Keeping

that as the foundation of this work, we offer some of the latest insights on the COVID-19 pandemic. We begin this paper with a comprehensive review of the COVID-19 itself, in which we explore its clinical features, transmission mechanism, and diagnosis procedures. Following this, we discuss the stages the disease goes through in the course of its spread. We also list the various treatment efforts being made to put an end to the pandemic and the preventive measures to be followed till the time that is possible. To calibrate the disastrous impact of the COVID-19, we also take a broad look at the state of the global economy following its outbreak. In the thorough discussion post this, we dissect the various technological interventions made in the direction of COVID-19 impact management. Primarily, our discussion focuses on the use of emerging technologies such as IoT, drones, AI, blockchain, and 5G in mitigating the impact of the COVID-19 pandemic. Till the time a cure for this disease surfaces, the responsibility to manage and limit its impact rests largely with these technologies.

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